TREATISE
ON
SEDIMENTATION

PREPARED UNDER THE AUSPICES OF THE COMMITTEE ON SEDIMENTATION, DIVISION OF GEOLOGY AND GEOGRAPHY, NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMY OF SCIENCES

BY

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Second Edition, Completely Revised

BALTIMORE

THE WILLIAMS & WILKINS COMPANY

1932

Made in the United States of America

First Edition, April, 1926
Second Edition, September, 1932

Composed and Printed at the
WAVERLY PRESS, INC.
for
The Williams & Wilkins Company
Baltimore, Md., U. S. A.

PREFACE TO FIRST EDITION

The preparation of this work was initiated in 1920 by the Committee on Sedimentation of the Division of Geology and Geography of the United States National Research Council which at that time formulated plans to undertake the preparation of a Treatise on Sedimentation and designated the writer to bring the work to materialization. After much correspondence and consultation it was decided that this could best be done by having different specialists submit manuscripts treating of those phases of sediments and sedimentation with which each was most familiar. Requests for this aid received very cordial responses. Many manuscripts have been received. Some of the contributions have been used with very little modification. In most cases it has been necessary to modify and abbreviate in the interest of keeping the book from reaching impossible proportions. In some instances the manuscripts have been made the basis for the preparation of a topic. Much of the book is the work of the writer and he assumes responsibility for any errors it may contain. Acknowledgments to the contributors are made in appropriate connections.

The method of construction was devised early in the history of the work and was submitted to the Committee on Sedimentation for approval. The method is open to criticism in that it makes necessary some repetition of statement. It has the merit of bringing together under a single topic the essential facts relating thereto. Moreover, this method of presentation has been used for five years in classes in the University of Wisconsin and has been found effective. Much elementary detail has been omitted on the assumption that the probable readers of the work would be familiar therewith.

The writer is indebted for illustrative material to the United States Geological Survey, to Dr. G. R. Mansfield and others. Acknowledgement for each illustration is made in connection therewith. The photographs for the topic on Carbonaceous Sediments were contributed by its author, Dr. David White, and Mr. C. K. Wentworth furnished the illustrations for his contributions on the Coarser Grained Clastics. Drs. E. M. Kindle and W. H. Bucher prepared the diagrams illustrating ripple mark.

Drs. N. M. Fenneman, A. C. Lawson and David White, successive Chairmen of the Division of Geology and Geography of the National Research

Council and Dr. T. Wayland Vaughan, former Chairman of the Committee on Sedimentation, have generously encouraged and aided the preparation of the work and its advancement to its present state of completion could not have been accomplished without the assistance of these men.

The preparation of this work has been a labor of love on the part of its authors. Each has given generously of his time in the hope that interest in sediments might be increased and research therein accelerated and has donated his financial interest in the book to the Committee on Sedimentation in order that the Committee might be enabled to perform its work more effectively.

Lastly, it is fitting that acknowledgments be made to the late Dr. Joseph Barrell whose inspiration and teaching during the last ten to fifteen years of his life led many to devote attention to the sediments. This inspiration still lives. It is the hope of the writers that this Treatise on Sedimentation is worthy of the teachings of Barrell and that its influence and the spirit which actuated its preparation may carry the geologic idealism of which he was a most prominent exponent.

W. H. TWENHOFEL.

July 1, 1925.

PREFACE TO SECOND EDITION

The preparation of the first edition of the Treatise on Sedimentation was initiated in 1920 at which time the Committee on Sedimentation of the Division of Geology and Geography of the National Research Council formulated plans for the preparation of such a book and instructed the writer to bring it to completion. The first edition, published in 1925, met with a ready sale and the first printing was soon exhausted. Preparation for the second edition was begun in 1926.

The plan of the second edition is the same as that of the first. This method of presentation has been followed for over twelve years in the classes in the University of Wisconsin and has been found effective. It is open to criticism in that it makes for some repetition but has the advantage of grouping the essential facts relating to any topic.

Preparation of the second edition has involved extensive search of the literature, particularly foreign. It is vain to hope that everything of importance has been seen in those literatures with the language of which the several contributors and the writer have familiarity. Literatures of unfamiliar languages have not received much consideration.

Several geologists participated in the preparation of the first edition and acknowledgments were made therefor. The manner of doing this, however, does not seem to have made clear to whom credit and responsibility were due. It is hoped that there is no doubt in the present edition. The manuscript for the topic on the "Carbonaceous Sediments" was prepared by Doctor David White of the United States Geological Survey. Students interested in this type of sediment should be deeply grateful to Doctor White as the work was done at a time when he was recovering from a serious illness and could devote not much more than an hour per day to work. The manuscript on "Manganese in Sediments" was prepared by Doctor D. F. Hewett, also of the United States Geological Survey. Doctor C. K. Wentworth of Washington University, St. Louis, Missouri, is responsible for the topic treating of the "Coarser-grained Clastic Sedimentary Products." Professor W. A. Tarr of the University of Missouri collaborated with the writer in the preparation of the manuscripts on "Flint and Chert" and "Concretions," and Professor Tarr prepared the manuscript on "Cone-in-cone." The manuscript on "Ripple Mark" is the work of Doctor E. M. Kindle of the Geological Survey of Canada and Professor W. H. Bucher of

the University of Cincinnati. It was the expectation that Professor Eliot Blackwelder of Stanford University would prepare the manuscript on "Phosphatic Sediments" and would collaborate with the writer in responsibility for the topic on the "Colors of Sediments." The state of Professor Blackwelder's health precluded his devoting effort to the task. The topic on the "Relation of Vertebrates to Sediments and Sedimentary Environments" is the work of the late Professor W. D. Matthew; this is unchanged and appears as in the first edition.

The writer is deeply indebted to Miss Clara Mae LeVene and Miss Vera A. Timm of New Haven, Connecticut, for their painstaking work in editing the manuscript, checking part of the references, and reading the proof.

The second edition contains almost double the number of illustrations of the first. As in the first edition, the illustrations are not balanced. No apology is made for this fact other than that it was felt that little would have been gained by the inclusion of illustrations on some phases of the subject. The illustrations have been acquired from many sources and acknowledgments are made in connection with each. Thanks are due to the different donors for their courtesies.

As in the first edition, the work on the revision has been a labor of love on the part of each contributor. No writer receives any financial return and the royalties are donated to the Committee on Sedimentation to further research in the field of sedimentation.

The writer again wishes to acknowledge his indebtedness to the late Professor Joseph Barrell from whom he gained his first appreciation of the problems connected with sediments. It is the writer's hope that Barrell's inspiration and the idealism of which he was a most worthy exponent may in some degree be expressed in the spirit that has actuated the preparation of the Treatise on Sedimentation and its first revision.

W. H. Twenhofel.

March, 1932.

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INTRODUCTION

Every rock is a response to a definite environment, its characters being adaptations to the various conditions and processes which existed at certain times and places. Some environments give rise to igneous rocks; others produce sedimentary rocks.

The destruction of igneous rocks and the reaggregation and consolidation of the resulting materials through surface agencies lead to the formation of rocks of the sedimentary group. If sedimentary rocks are subjected to the conditions resulting in fusion, the rocks lose identity, and when the fused mass is cooled, an igneous rock is produced. This sequence of change from igneous to sedimentary rocks and thence back to igneous rocks constitutes the metamorphic cycle. The first change is characterized by destructive processes and is known as katamorphism; the second is characterized by constructive, or anamorphic, changes. The local completion of the cycle is suggested by numerous facts, and many rocks have progressed far in the second half of the cycle. At every point in the cycle the rock materials have some characteristics inherited from previous states and others due to conditions existing at that point.

Sedimentation includes that portion of the metamorphic cycle from the destruction of the parent rock, no matter what its origin or constitution, to the consolidation of the products derived from that destruction (with any additions from other sources) into another rock. It thus involves a consideration of the sources from which sediments are derived; of the methods of transportation from the places of origin to those of deposition; of the agents, methods, and environments of deposition; of the nature of the mineral and other materials composing the sediments; of the chemical and physical changes modifying the sediments from their production to their ultimate consolidation; of the climatic and other environmental conditions prevailing at the places of origin, in the regions through which transportation takes place, and at the sites of deposition; of the structures developed in connection with deposition and consolidation; and of the horizontal and vertical variations of the materials deposited.

Sediments are defined as deposits of solid material (or material in transportation which may be deposited) made from any medium on the earth's surface, or in its outer crust under conditions of temperature approximating

those normal to the surface.[1] Some transportation is involved, but it may range from mere detachment of the particles from the parent rock to movement over many miles; it must, however, have been sufficiently great to destroy textures and structures of the parent rock, except as these are preserved in the particles. The solid matter may be of organic or inorganic origin. The condition of temperature approximating that normal to the surface excludes from sediments the precipitates from magmas, but includes those from water of surface temperatures, although it is recognized that the processes involved in precipitation from surface waters are much the same as those in magmas and hot waters. The medium may be air, water, or ice, and the agents of transportation may be any of those operating upon the earth's surface. Not limiting the place of deposition to the surface of the earth permits the inclusion of the deposits of caves and smaller cavities and the cementing material which is brought in by waters of surface temperatures, but excludes the deposits made by highly heated waters, although it is granted that these are not sharply separated from those made by waters of lower temperatures. The materials ejected from volcanoes are considered sediments if their temperatures at the times of deposition are sufficiently low not to be important factors in consolidation. Under all conditions, the type and extent of a sediment which may be deposited is a consequence of the environment, from which it follows that the various components of environments to some degree are reflected in the sediments therein formed. Some sediments are extremely sensitive to environmental factors; others are less so, but no sediments are independent of the environments or can be deposited in several environments unless some differences occur.

The study of sedimentary rocks has not kept pace with that of igneous rocks. Petrology as a division of geology has, in fact, been limited largely to igneous rocks. The general inability to observe the igneous rocks in process of formation appears to have lent enchantment to their study, whereas the sedimentary rocks, forming almost at the petrologist's door and certainly about the region of his home, have received scant consideration, and in many instances have not been noticed. Moreover, the processes of sedimentary rock formation have been considered simple. It appeared obvious that sands ultimately become sandstone, muds become clay and shale, and shells consolidate to form limestone, and little thought was given to the factors responsible for the existence of these rocks. It is now appreciated, however, that this conception of the simplicity of sediments and

[1] Modified from the definition of Andrée, K., Geol. Rundschau, Bd. 3, 1912, p. 338.

sedimentary rocks is not correct and that each sedimentary rock is the product of a long series of complex processes.

The study of sediments has been approached through the door of stratigraphy, but the methods of the sedimentationist and the stratigrapher are different—the latter studies sequences of sediments and endeavors to interpret the conditions under which they were deposited; the former studies the production of sediments and carries his conclusions into the interpretation of sequences. He endeavors to obtain "a more accurate and quantitative knowledge of that earth history which is now being recorded in order to obtain a more accurate knowledge of the past."[2] The study of any particular sediment requires a consideration of its origin and source, the processes of transportation and deposition, the environment in which deposition took place, the changes occurring after deposition, and the individual characteristics of the sediment.

Of the several works dealing with sediments along these lines the most important are Collet's "Les Dépôts Marins," Grabau's "Principles of Stratigraphy," Walther's "Einleitung in die Geologie," Cayeux' "Étude Pétrographique des Roches Sédimentaires" (1916) and "Les Roches Sédimentaires de France" (1929), Murray and Renard's "Deep Sea Deposits" of the "Challenger" Reports, Andrée's "Geologie des Meeresbodens," "Grundzüge der Geologie" by Salomon and his collaborators, and Marr's charming work on "Deposition of the Sedimentary Rocks." These are more or less incomplete in several phases of the field of sedimentation, and some of them, in addition, contain material only remotely, if at all, related to that subject.

[2] Barrell, J., Criteria for the recognition of ancient delta deposits, Bull. Geol. Soc. Am. vol. 23, 1912, p. 446.

CHAPTER I

SOURCES AND PRODUCTION OF SEDIMENTS

The sources of sediments are (1) terrigenous, (2) organic, (3) volcanic, (4) magmatic, and (5) cosmic. These are considered in the order named.

SEDIMENTS OF TERRIGENOUS ORIGIN

Terrigenous sediments, those resulting from rock destruction, vary with the rocks from which they are derived, the topographic relief of the region where the parent rocks occur, the distances of the sites of deposition from the places where the sediments are formed, the methods by which the rocks are destroyed, the time intervening between the production of the sediments and their deposition, and the climatic and other conditions from the regions of rock destruction to those of deposition. A rock is likely to produce different varieties of sediment in a warm and in a cold climate, in a dry and in a wet climate, after a long and after a short haul, and after destruction by one method rather than by another. An inquiry into the sources and production of terrigenous sediments resolves itself into four divisions: (1) the character of the rocks from which sediments are derived; (2) the methods of rock destruction; (3) the factors modifying the methods of rock destruction; and (4) the immediate sources of sediments. Divisions (1), (2), and (4) are considered in this chapter.

THE CHARACTERS OF THE ROCKS FROM WHICH SEDIMENTS ARE DERIVED

The rocks of the earth's crust fall into two groups—igneous and sedimentary. The igneous rocks have solidified from a liquid state; the sedimentary rocks have resulted from the integration of the products of destruction of other rocks. Descriptions of igneous rocks are not given, it being assumed that the student is familiar with their properties.

According to Clarke and Washington,[1] the rocks of the lithosphere are 95 per cent igneous and 5 per cent sedimentary, the latter being estimated by weight as 82 per cent shale, 12 per cent sandstone, and 6 per cent limestone.[2] From these figures it might appear that most sediments now forming have been derived from igneous rocks. This might have been the

[1] Clarke, F. W., and Washington, H. S., The composition of the earth's crust, Prof. Paper 127, U. S. Geol. Surv., 1924, p. 34.

[2] Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 61, 319.

case during some periods of geologic time and might have obtained in the beginning, but at the present, and probably during most of geologic time, the major portion of the surfaces of the continents has been covered with sedimentary rocks, and it is from these that later sediments have been derived. Clarke,[3] using the estimates of A. von Tillo, states that at the present time the earth has 75 per cent of its surface underlain by sedimentary rocks and 25 per cent underlain by igneous rocks, and it is not unlikely that the average has approximated these figures throughout much of geologic time. Thus one reaches the inference that, since at least the beginning of the Paleozoic, the sediments, in large and perhaps major part, have been derived from pre-existing sediments, or, as Barrell has stated it, "more than half, perhaps four fifths, of the erosion of igneous rocks was accomplished before the beginning of the Paleozoic."[4]

For immediate purposes the sedimentary rocks may be divided into the carbonate or limestone group, including rock salt and gypsum; the sand and gravel group; and the mud or clay group. The sandstones are largely composed of quartz; the limestones of calcite and dolomite; and the mud and clay rocks of aluminum hydrates, iron oxides and hydroxides, and finely ground up materials of great variety.

The ranges in chemical and mineral composition of igneous and sedimentary rocks are shown in table 1.[5] Column A of this table gives the composition of the average igneous rocks as based on analyses made in the laboratories of the United States Geological Survey.[6] By a graphical method Mead[7] found that a combination of 65 parts granite and 35 parts basalt would yield results in best accord with the estimated average composition of sedimentary rocks, and the average analysis of granite and basalt combined according to this ratio is given in column B of table 1.

Table 2 gives composite analyses of each of the three divisions of sedimentary rocks.[8] The average mineral compositions of the igneous and sedimentary rocks are given in table 3.[9]

Minor constituents have been omitted from the tables, but small percentages of zirconium, chlorine, fluorine, sulphur, chromium, barium, strontium, lithium, and other substances may be present.

It is the destruction of the igneous and sedimentary rocks, or their modified equivalents, that produces the terrigenous sediments. Sediments

[3] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 120.
[4] Barrell, J., in The evolution of the earth and its inhabitants, 1919, p. 56.
[5] Clarke, F. W., op. cit., pp. 441, 459, 465, 468.
[6] Clarke, F. W., op. cit., p. 26.
[7] Mead, W. J., The average igneous rocks, Jour. Geol., vol. 22, 1914, pp. 772–787. Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, p. 66.
[8] Clarke, F. W., op. cit., p. 30.
[9] Leith, C. K., and Mead, W. J., op. cit., pp. 74, 76.

TABLE 1

COMPOSITION OF IGNEOUS ROCKS

	GRANITE	DIORITE	GABBRO	PERIDOTITE	A	B
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
SiO_2	74.37	57.97	55.87	39.37	61.69	63.18
Al_2O_3	13.12	15.65	13.52	4.47	15.47	15.35
Fe_2O_3	0.73	0.73	2.70	4.96	2.71	2.97
FeO	0.87	2.80	5.89	9.13	3.54	3.35
MgO	0.35	4.96	6.51	26.53	3.87	2.79
CaO	1.26	10.93	8.87	3.70	4.98	4.58
Na_2O	2.57	3.03	2.42	0.50	3.48	3.28
K_2O	6.09	3.16	1.72	0.26	3.14	3.24
TiO_2	0.29	0.60	0.56	0.66	0.82	
P_2O_5	0.06	0.15	0.25	0.17	0.30	
	99.71	99.98	98.31	99.75	100.00	98.74

TABLE 2

COMPOSITION OF SEDIMENTARY ROCKS

	COMPOSITE ANALYSES OF 253 SANDSTONES	COMPOSITE ANALYSES OF 78 SHALES	COMPOSITE ANALYSES OF 345 LIMESTONES
	per cent	*per cent*	*per cent*
SiO_2	78.66	58.38	5.19
TiO_2	0.25	0.65	0.06
Al_2O_3	4.78	15.47	0.81
Fe_2O_3	1.08	4.03	0.54*
FeO	0.30	2.46	
MnO	Trace	Trace	0.05
CaO	5.52	3.12	42.61
MgO	1.17	2.45	7.90
K_2O	1.32	3.25	0.33
Na_2O	0.45	1.31	0.05
Li_2O	Trace	Trace	Trace
H_2O	1.64†	5.83†	0.77†
P_2O_5	0.08	0.17	0.04
CO_2	5.04	2.64	41.58
S			0.09
SO_3	0.07	0.65	0.05
Cl	Trace		0.02
SrO	Trace	Trace	None
BaO	0.05	0.05	None
	100.41	100.46	100.09

* Includes Fe_2O_3 and FeO.

† Includes organic matter.

derived from igneous rocks contain, as a rule, a greater variety of mineral particles than those derived from sedimentary rocks, due to the fact that the latter, having been subjected to the processes of rock destruction for a longer time than the former, are likely to have had the less stable constituents removed.

TABLE 3

AVERAGE IGNEOUS ROCK Granite, 65 per cent Basalt, 35 per cent		COMBINED SEDIMENTS Shale, 82 per cent Sandstone, 12 per cent Limestone, 6 per cent	
	per cent		*per cent*
Albite	25.60	Quartz	34.80
Anorthite	9.80	Kaolin	9.22
Orthoclase	14.85	White Mica	15.11
Biotite	3.86	Chlorite	5.29
Muscovite	3.85	Limonite	4.00
Hornblende	1.60	Dolomite*	9.07
Augite	12.90	Calcite	4.25
Olivine	2.65	Gypsum	0.97
Quartz	20.40	Orthoclase	11.02
Magnetite	3.15	Albite	4.55
Titanite and Ilmenite	1.45	Magnetite	0.07
	100.11	Rutile	0.55
		Ilmenite	0.02
		Apatite	0.35
		Carbon	0.73
			100.00

* Includes a small quantity of $FeCO_3$.

ROCK DESTRUCTION (KATAMORPHISM)[10]

Rock destruction, or katamorphism, is of two general forms: (1) breaking into smaller pieces which are the individual minerals or fragments of the parent rock, and (2) separation into smaller pieces which in some degree have a mineralogical composition different from that of the parent rock. The former is physical destruction; the latter chemical. The former is rock breaking, or disintegration; the latter is rock decay (rock rotting), or decomposition. The two processes generally proceed simultaneously, but the effects of one or the other may dominate in the end products. Students have not always discriminated between the two processes, and instances are not few where the terms have been incorrectly used.

[10] For detailed treatment of the subject of rock destruction see Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 3–99; Merrill, G. P., Rocks, rock weathering, and soils, 1906, pp. 150–273; Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 24, 1913, pp. 241–255, and vol. 25, 1914, pp. 229–247.

Rock Breaking (Disintegration)

Rock breaking, or disintegration, may result from expansion and contraction of rocks caused by changes of temperature; from abrasion due to wind, water, ice, etc.; from grinding; from impact; from undermining; from development of minerals within rocks; from rifting effects of roots and ice; and from earth movements.

Rock Breaking Due to Changes of Temperature (Insolation). Minerals do not have the same coefficients of expansion, and their absorption of heat varies with their colors. Rocks on and near the surface are subjected to an annual range of temperature, with daily fluctuations within this range. A rising temperature leads to mineral expansion, a falling temperature to mineral contraction. The dark-colored minerals, because of greater heat absorption, may expand and contract more than those of lighter colors. As surface temperatures over many parts of the earth have considerable daily and seasonal variations, these being greatest in high altitudes, in regions with little cloudiness, and in arid regions, expansion and contraction are often repeated, and ultimately the natural bonds of the minerals are destroyed and the rocks separate into their constituent minerals. As many minerals have coefficients of expansion which are different in directions parallel to the different axes, and as there usually is little uniformity of crystal orientation in rocks, the results of expansion and contraction in the rock minerals are more or less the same for rocks composed of one mineral as for those composed of two or more. Thus, Ordovician limestones in northern Kentucky which had been exposed on the surface for perhaps a score of years became an aggregate of loosely interlocked crystals of calcite, and Trenton dolomites near Blue Mounds, Wisconsin, have fallen apart into the separate rhombohedrons of the composing mineral. This form of rock breaking, in which the rock becomes separated into its constituent minerals, may be designated *granular, or mineral disintegration* in contrast to that form of rock breaking in which the fragments are merely pieces of the parent rock and like it in mineral constitution. This second form will be designated *block disintegration*. Both forms are thought to proceed more or less simultaneously.

Changes of temperature may also produce block disintegration. Sudden changes, such as may be caused by insolation, by cold rain falling on hot rock, or by fire, produce rapid local expansion or contraction, and it is thought that breaking is almost as certain as it would be in a glass vessel subjected to sudden changes of temperature. The effects of local, or differential expansion may be demonstrated by throwing a piece of flint into a camp fire, whereupon sharp reports may result, and small fragments may

be hurled considerable distances. Camp fires on rocky beaches often surprise their builders with the small explosions. Primitive and backward peoples in different parts of the world have used fire, and the resulting differential expansion, to quarry rocks of various kinds.[11] In arid regions rocks are known to become so heated on those surfaces which face the direct rays of the sun as to be uncomfortable to touch, and a cold rain falling upon such heated surfaces must lead to considerable breakage. Prairie and forest fires cause great temperature changes in a short time over extensive regions, and the affected rocks break into curved scales or plates. Fires must have been frequent subsequent to the development of considerable upland vegetation, and much rock disruption must have been caused by them. Experiments conducted by R. Loofbourow under the direction of Blackwelder showed that most rocks can withstand rapid cooling and heating through a range of 300°C. and all of them through a range of 200°C. and as insolation does not exceed 70°C. the latter concluded "that insolation, or diurnal changes of temperature, are entirely inadequate to cause rock breaking";[12] it seems, however, that there are too many recorded occurrences of rock breaking in accord with the traditional view to permit the complete acceptance of Blackwelder's generalization.[13] That fire is an agent of great importance in some regions is certain, but there are too many regions without fire where rock breaking is known to occur, and it does not seem possible to refer this to any agent other than temperature change.

In general, rocks are poor conductors of heat. This being so, the outside or exposed parts of a rock become warm and expand under the heat of the sun before the inside is warmed, with the result that fractures may develop somewhat parallel to the surface. Eventually there may be passage of heat into the interior of the rock, which may become almost as warm as the exterior. If, then, the surroundings cool, the exterior may cool more rapidly than the interior, and the shell previously separated may contract and become too small for the interior, leading to the development of radial fractures. The exterior, being thus broken radially and tangentially, in time separates from the interior, the process being known as *exfoliation*. As later noted, this is partly decomposition.

The breaking of rocks because of expansion often is beautifully shown by cement streets and sidewalks. On a street near Madison, Wisconsin, on a very hot day in July, 1927, at the junction of two concrete blocks, pieces ranging from 6 inches to a foot in diameter and with an approximate thick-

[11] Warth, H., Nature, vol. 51, 1895, p. 272.

[12] Blackwelder, E., Fire as an agent in rock weathering, Jour. Geol., vol. 35, 1927, pp. 134–140.

[13] Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 24, 1913, pp. 245–250.

ness of an inch broke away from the concrete beneath with sufficient force to hurl themselves over a radius of several feet. A similar occurrence took place on the same pavement on the morning of June 24, 1931. This pavement was laid in 1920 and the postponement of breakage for seven years in one case and eleven in the other shows that the factor of time is important. Perhaps chemical action aided in weakening the bonds at the places of breaking.

If the changes of temperature cross the freezing point, the freezing of water in the pores, cracks, and other openings of the rocks introduces a powerful agent of disintegration. Small-pored but permeable rocks may suffer more than those with larger openings. This water either enters the rocks from external sources, or, rarely, is imprisoned in the minerals at the time of formation, the volume of such imprisoned water in some instances being 5 per cent of that of the minerals.[14]

In regions where cold seasons follow moist ones, the coming of frost finds the rocks saturated with water, and rock breaking is great in consequence. Effects rising from this cause may be seen on the brick-paved streets of almost any city within the latitudes of frost, some bricks of high porosity having crumbled in a single winter. At Madison, Wisconsin, drain tile left on the ground, in early November, 1920, had crumbled in late January, 1921. Merrill states that blocks of rock exceeding 6 feet in diameter on Behring Island, Alaska, which showed no trace of disintegration in November 1882, seven months later had split up into sharp-edged fragments 2 inches in dimension, although still remaining in position in the parent blocks.[15] Cape Sand Top on the northeast corner of Anticosti Island has its surface covered with tons of sharp-edged fragments of limestone which have developed in this way. Similar effects on Ordovician limestones occur at Point Rich on the west coast of Newfoundland and on the top of the limestone cliffs and raised beaches of the Mingan Islands.

Disintegration from freezing annually crumbles the clays within the depth of its influence, and after freezing, clay soils collapse and have their permeability reduced.

Under many conditions where changes of temperature and freezing disintegrate rock, the fine particles are blown away as rapidly as produced, and only those fragments too large for the wind to transport are left. Such is the case at Cape Sand Top, Point Rich, and many places on the raised beaches of the Mingan Islands.

Depth of disintegration through changes of temperature and freezing. Rock breaking due to changes of temperature above the freezing point can extend

[14] Merrill, G. P., Rocks, rock weathering and soils, 1906, p. 178. Quoted from Sorby.
[15] Merrill, G. P., op. cit., p. 178. Quotation from letter of Dr. L. Stejneger.

to very shallow depths, since with depth the range in temperature becomes less. Hence the continuation of rock breaking from this cause depends upon the progressive removal of the broken materials. Rock breaking due to freezing extends to greater depths, but the results are significant only in cases of repeated freezing and thawing, as permanent freezing produces little effect.

Regions of most apparent effects. Granular and block disintegration are most conspicuous in regions where the greatest and most frequent changes of temperature occur, and the results are greatest where the conditions are such that the products of disintegration do not remain over the places of production. The most favorable conditions occur in those regions which are either too cold or too dry to permit the development of a protecting cover of vegetation, where steep slopes have the débris removed by gravity, and where the winds are sufficiently strong to blow away the fine materials as rapidly as such are produced.

ROCK BREAKING DUE TO UNDERMINING, WEDGE EFFECTS OF ROOTS, AND GROWTH OF MINERALS. The undermining done by streams, winds, waves, etc., leads to rock falls and slides, with more or less rock breaking. Some rock breaking is also accomplished by the wedge work of roots, but it does not seem likely that the quantity is great. A certain amount of disintegration is accomplished near the surfaces of rocks through the formation of new minerals, as may occasionally be observed on concrete walls. Lucas[16] considered the crystallization of salts in rocks an important agent of disintegration in Egypt; Jutson[17] has described cavities near the bases of cliffs in western Australia whose origin he refers to the rifting work of salts deposited in the rocks through the evaporation of the water in which they had been dissolved. Similar effects produced by calcite have been described by Rothrock from Oklahoma.[18] The breaking of rocks in this manner may be observed experimentally by placing potassium hydroxide on a porcelain plate, from which in the course of several days the enamel will be pried away beneath those places where the salt rested.

ROCK BREAKING THROUGH CRUSTAL MOVEMENT. Broad areas of the earth's crust have been extensively crushed, and the rocks thus broken have been exposed by various agents and large volumes of rock fragments made available for sediments. The quantity thus broken which may enter into sedimentary deposits with little change is difficult of quantitative statement, but it must be large. It has been stated that under the condi-

[16] Lucas, A., The disintegration of building-stones in Egypt, Survey Dept., 1902. The process was designated "exsudation."

[17] Jutson, J. T., The influence of salts in rock weathering, Proc. Roy. Soc. Victoria, vol. 30, pt. ii, 1918, pp. 165–172.

[18] Rothrock, E. P., Jour. Geol., vol. 33, 1925, pp. 80–83.

tions of the western American deserts chemical changes and mechanical breaking due to diastrophism "are far more effective in rock destruction than all other agents combined."[19] The generalization seems too far reaching; it certainly applies in many localities.

ROCK GRINDING. As defined by Marshall,[20] grinding "is the crushing of small grains by the continued contact and pressure of pebbles of relatively large size," and in his experiments it was the most rapid action, reducing the small constituents of an aggregate to much smaller dimensions in short periods of time. The products range from rock flour to larger dimensions. Marshall concluded "that when gravel from $\frac{3}{4}$ of an inch upwards is moving on a beach, the fine gravel, $\frac{1}{10}$ of an inch and less must soon be eliminated," and "cannot live on a beach where wave action keeps gravel in movement."

ROCK ABRASION. Rock abrasion is accomplished on the earth's surface by water, wind, ice, and animals, in each case most of the actual work being done by rocks rubbing on each other without crushing. Rock flour is the product. Abrasion by water has been studied experimentally by Daubrée, Munier, Wentworth, Marshall, and others. Daubrée,[21] rolling fragments of feldspar in a revolving cylinder, found that the fragments became rounded and a fine impalpable mud was obtained. Granites similarly treated had the feldspar reduced to fine mud, and the mica to minute shreds, and the quartz rounded to sands which could not be reduced to dimensions lower than one fourth millimeter. In Wentworth's experiments,[22] fragments of Niagara limestone of the weight of 180 grams each were rolled for 700 miles, the reduction averaging 177 grams per fragment, or about 1 gram for each 4 miles. It is possible that in swift sand- and silt-laden waters the reduction would be more rapid. Marshall mixed materials of different dimensions, deriving these materials from New Zealand beaches,[23] and found that the loss by abrasion of pebbles of hard rock amounted to 1.5 per cent in 24 hours, the travel during this time being equivalent to 24 miles.

Large volumes of rock flour are produced by glacial abrasion and grinding. A glacier may be compared to a gigantic file or rasp whose teeth are the imbedded rock fragments which, held against the rock floor, scratch and polish it under a pressure that for ice a mile thick exceeds 300,000 pounds per square foot. Grooves 20 feet or more wide and 1 to 3 feet deep have been cut in this way on hard limestones on the Mingan Islands.

[19] Blackwelder, E., Desert weathering, Abstract, Bull. Geol. Soc. Am., vol. 38, 1927, pp. 127–128.

[20] Marshall, P., The wearing of beach gravels, Trans. New Zealand Inst., vol. 58, 1927, p. 518.

[21] Daubrée, A., Études synthétiques de géologie expérimentale, 1879, p. 268.

[22] Wentworth, C. K., A study of cobble abrasion, Jour. Geol., vol. 27, 1919, pp. 507–521.

[23] Marshall, P., op. cit., pp. 507–532.

Some abrasion takes place in the digestive tracts of some modern echinoids, many birds, and some modern reptiles, and it is known that certain of the Mesozoic dinosaurs used stones in their digestive organs. The quantity of abraded material thus produced cannot be given quantitative statement, but it may be large.[24]

Immense quantities of fine material are produced by wind abrasion, and due to the absence of water around the abraded particles, it is believed that they may be reduced to smaller dimensions than may be done by water.

Some of the particles produced by abrasion and grinding are of colloidal dimensions. In experiments conducted by Lenher[25] and Town, quartz sands and large round pieces of quartz were ground for 400 hours in an Abbe ball mill. Of the fine material developed in the grinding, 85 per cent had diameters less than 0.004 mm., and 15 per cent diameters between 0.004 and 0.016 mm. Similar results were obtained with orthoclase.

Marshall,[26] using 5000 grams of mixed gravels in a Deval machine for 24 hours with 2 liters of water, the gravels traveling at the rate of approximately 1 mile per hour, produced 307 grams of materials with diameters less than 0.07 mm., a part of which, however, was not derived from the gravel but from the machine. Some of this fine material was of colloidal dimensions. It seems certain that in nature many relatively insoluble substances are mechanically reduced to the dimensions of colloids, and the quantities of this character may be large.

ROCK IMPACT. Impact produces particles of a wide range of dimension, which for small particles of quartz are tiny flakes with sharp edges and curved surfaces, the flakes having large area with respect to volume. They form a part of what Reade and Holland[27] have called "quartz dust." In many cases impact does not lead to separation but to minute fracture whose presence favors frost action and decomposition. On the shores of seas and lakes and in torrential streams, impact occurs between large blocks and between such blocks and the shores; fragments of large dimension are produced, many of which are marked by the small crescentic fractures known as chattermarks.

Experiments conducted by Marshall[28] showed that impact acts more

[24] Kindle, E. M., A neglected factor in the rounding of sand grains, Am. Jour. Sci., vol. 47, 1919, pp. 431–434.

[25] Lenher, V., Silicic acid, Jour. Am. Chem. Soc., vol. 43, 1921, pp. 391–392.

[26] Marshall, P., Colloid substances formed by abrasion, Trans. New Zealand Inst., vol. 59, 1928, pp. 609–613.

[27] Reade, T. M., and Holland, P., Sands and sediments, pt. iii, Proc. Liverpool Geol. Soc., pt. ii, vol. 10, 1905, p. 155.

[28] Marshall, P., The wearing of beach gravels, Trans. New Zealand Inst., vol. 58, 1927, p. 518.

rapidly than abrasion "when the impactor has ten times or more the diameter of the impactee," that rocks may be broken by impact sixteen times as rapidly as by abrasion, and that grinding acts two and a half times as rapidly as impact.[29] The small particles produced by impact and those due to abrasion and grinding may remain in suspension in both air and water for a long time, and thus may attain wide distribution.[30]

Rock Breaking Due to Glacial Plucking and Crushing. The great weights of glaciers probably lead frequently to rocks being crushed, and their plucking action removes extremely large blocks from original positions. The quantity thus placed in transportation may be large.

Summary of Results of Rock Breaking. As a consequence of disintegration through the agents and processes considered, there are produced: (1) very finely divided materials of colloid to silt dimensions, and if not affected by decomposition, this material is composed of the same materials as the rocks from which it was derived; (2) somewhat coarser materials of sand and granule size which are composed of the individual minerals of the parent rock; and (3) coarse fragments of pebble, cobble, and boulder dimensions which in many instances have the same mineral constitution as the parent rocks. If the sites of deposition are near to the places of origin, the materials deposited are very like the parent rock in mineral composition. If there has been much transportation, there is probably an intermingling of materials from many sources. The internal physical characteristics of the fragments and the presence of certain mineral constituents may permit the determinations of some of the sources.

Rock Decomposition (Rock Rotting)

Rock decomposition implies that the materials of the parent rock have undergone chemical change. Disintegration to a great extent paves the way for decomposition, as the rock surfaces are thus greatly increased, and decomposition, which is more or less proportional to surface, is multiplied accordingly.

The minerals of a rock suggest the resulting products. Quartz may remain unchanged. The silicates ordinarily decay to hydrous aluminum silicates, as kaolinite and allophanite (siallites),[31] to various oxides, and to carbonates. Carbonate rocks usually leave little more than residual material derived from their insoluble contents. Most rocks contain small quantities of various minerals whose release from the rocks without decomposition adds little to the volume of the products, but whose occurrence

[29] Marshall, P., op. cit., p. 519.
[30] Reade and Holland, op. cit., pp. 132–156.
[31] Harrassowitz, H., Laterit, Fortschr. d. Geol. u. Palæont., Bd. 4, Heft 14, 1926, p. 255.

therein may aid in the discovery of the source materials. The hydrous aluminum silicates may further decompose to form aluminum and other hydroxides (allites), and quartz, the products being laterite and bauxite,[32] and the processes being termed laterization. According to Mead,[33] laterization depends on the maintenance of an open texture in the clays, thus permitting circulation. As frost destroys the open texture of fine-grained materials, it was suggested that laterization is restricted to tropical and subtropical regions. Holland[34] referred laterization to the work of microorganisms, a view previously expressed by Passarge.[35] Fox's[36] explanation of laterization requires a tropical climate subject to alternations of dry and wet seasons or monsoons, a level or nearly level elevated land not subject to much physical erosion, rock suitable for leaving residues of alumina and ferric oxides, maintenance of open texture in the decomposing materials, water to remain for long times in the decaying materials and these to alternate with times when the interstices are empty, and a long time. Glinka considered laterite as the product of the tropical forest.[37] The original silicates may also directly decompose to quartz and aluminum hydroxide. Under the conditions of laterization the common end-products thus would be quartz, iron oxide and hydroxides, aluminum hydroxides, and carbonates, the last usually carried off in solution. The material remaining at the place of decay is known as laterite, which ordinarily contains some titanium and manganese oxides and ranges from laterites that are almost entirely oxides and hydroxides of iron to those that are very largely aluminum hydroxide.[38]

Decomposition results in increase in both weight and volume of the total materials produced as compared with the original rock, due to additions of H_2O, CO_2, SO_3, C, and O from the hydrosphere and atmosphere; this increase in the average igneous rock amounting to 5.30 grams of CO_2, 1.99 grams of H_2O, 0.30 grams of SO_3, 0.72 grams of C, and about 1 gram

[32] Harrassowitz, H., op. cit., p. 5. Harrassowitz defines laterite as a rock formed mostly out of crystalline dehydrated clay, and bauxite as a rock composed mostly of colloidal monohydrate clay. He states it forms in dry inland regions.

[33] Mead, W. J., Occurrence and origin of the bauxite deposits of Arkansas, Econ. Geol., vol. 10, 1915, pp. 22–55; Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 25–37

[34] Holland, T. H., On the constitution, origin and dehydration of laterite, Geol. Mag., vol. 40, 1903, pp. 49–69.

[35] Passarge, S., Über Laterite und Roterden in Africa und Indien, Rept. Sixth Intern. Geog. Cong., 1895.

[36] Fox, C. S., Bauxite, London, 1927, pp. 72–93. This work and that by Harrassowitz should be consulted for detail.

[37] Glinka, K. D. The great soil groups of the world and their development, Transl. by Marbut, C. F., 1928, p. 47.

[38] Fermor, L. L., What is laterite?, Geol. Mag., vol. 48, 1911, p. 400.

of O, or a total of 9.36 grams.[39] Much of the decomposed material is removed on, or shortly after, production, and the material left where the rock has decayed may be only a small per cent of the original rock. The losses in a granite[40] and an Hawaiian lava[41] are shown in the two analyses of

TABLE 4

	(1) FRESH GRANITE	(2) DECOMPOSED GRANITE	GAIN OR LOSS
	per cent	*per cent*	*per cent*
SiO_2	68.75	38.50	Loss 30.25
Al_2O_3	17.59	17.59	Loss 0.00
Fe_2O_3	1.40	1.29	Loss 0.11
MgO	0.64	0.11	Loss 0.53
CaO	3.25	0.51	Loss 2.74
Na_2O	4.54	1.29	Loss 3.25
K_2O	3.27	1.63	Loss 1.64
H_2O	0.56	6.59	Gain 6.03
	100.00	67.51	
	(3) LAVA	(4) DECOMPOSED LAVA	
SiO_2	52.45	5.82	Loss 46.63
Al_2O_3	11.49	11.49	Loss 0.00
Fe_2O_3	3.66	4.30	Gain 0.64
FeO	6.90	0.91	Loss 5.99
Mn_2O_3	0.36	0.05	Loss 0.31
CaO	10.32	0.10	Loss 10.22
MgO	5.81	0.06	Loss 5.75
Na_2O	2.44	0.08	Loss 2.36
K_2O	0.89	0.07	Loss 0.82
SO_3	0.20	0.22	Gain 0.02
P_2O_5	0.38	0.07	Loss 0.31
TiO_2	4.07	1.36	Loss 2.71
H_2O	1.02	4.87	Gain 3.79
	99.99	29.40	

table 4, the first and second of fresh and partially decomposed granite from 15 and 5 feet below the surface respectively, the third of fresh lava, and the

[39] Leith and Mead, op. cit., p. 81.

[40] Watson, T. L., Granites and gneisses of Georgia, Bull. 9A, Geol. Surv. Georgia, 1902, p. 312; Leith and Mead, op. cit., p. 8.

[41] McGeorge, W. T., Composition of Hawaiian soils, Bull. 42, Hawaiian Agric. Exper. Station, 1917, p. 6. Decomposed lava recalculated.

fourth of decomposed portions of the same rock. The figures are in terms of 100 grams of the fresh rocks and are calculated on the basis of the alumina remaining constant, this oxide being used because of its relative insolubility as compared with the others.

It is to be observed that in the decomposition of the granite there has been a great loss of silica, lime, soda, and magnesia, but that only about half of the potash has been removed. In the lava there has also been a great loss of potash. The potash, and to some extent the magnesia, have been thought to owe their retention to the facts that they form secondary minerals (as sericite) which are relatively stable under surface environments, and that the colloidal matter in the products resulting from rock destruction has high adsorption for these substances. The organic colloids which constitute parts of the soil possibly have a like effect.[42]

Decomposition may be so complete that all original materials of the parent rock are destroyed. If no transportation intervenes, the transition from the completely decayed rock to the undecayed parent can generally be traced, and the origin established. After transportation has occurred, this is hardly possible, and doubt will exist as to the kinds of rocks from which the materials were derived and the regions from which they came. Ordinarily, decomposition is not complete and the more resistant minerals persist. These usually are few in quantity, but their presence may serve to locate the sources (provenance, distributive province)[43] of the sediments and thus permit the unraveling of the ancient geography. Much careful work has been done in this respect by the Europeans, with extremely valuable results.[44] The decomposition of igneous rocks commonly leaves a greater residue of undecomposed minerals than is the case when sedimentary rocks decompose, as the latter have passed through at least one cycle of previous decomposition. Also, sediments derived from igneous rocks contain a greater varietal aggregate than do those derived from sedimentary rocks, and the former have a greater variety of the relatively stable minerals. The same applies to the products of disintegration.

[42] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 504–505.

[43] Brammall, A., Dartmoor detritals, a study of provenance, Proc. Geologists' Assoc., vol. 39, 1928, pp. 27–48; Milner, H. B., Sedimentary petrography, 2nd. ed., 1929.

[44] Mackie, W., The heavy minerals in the Torridon sandstones and metamorphic rocks of Scotland, and their bearing on the relative ages of these rocks. Read before Edinburgh Geol. Soc., Nov. 11, 1926, Abstract, Geol. Mag., vol. 64, 1927, pp. 141–142. Boswell, P. G. H., The petrography of the sands of the Upper Lias and Lower Inferior Oolite in the west of England, Geol. Mag., vol. 61, 1925, pp. 246–264. See also other papers by Boswell. Smithson, F., Geological studies in the Dublin District, I. The heavy minerals of the granite and contiguous rocks in the Ballycorns District, Geol. Mag., vol. 65, 1928, pp. 12–25. Thomas, H. H., The mineralogical constitution of the finer material of the Bunter pebble-bed in the west of England, Quart. Jour. Geol. Soc., vol. 58, 1902, pp. 620–632.

AGENTS AND PROCESSES OF ROCK DECOMPOSITION. Decomposition is brought about by gases of the atmosphere, these gases dissolved in water, the water itself and substances therein, and organic matter. Oxidation, hydration, carbonatization, and solution are the four processes which are chiefly responsible for rock decay. Organic matter and the acids produced in plant growth and those arising from decomposition play a considerable, but an undetermined, rôle.[45]

Swamp or peat waters are rather strongly solvent. It has been claimed that this is due to contained carbon dioxide,[46] but such waters may contain acids which are the result of bacterial decomposition, e.g. formic, acetic, butyric, succinic, lactic, and valeric,[47] to which the solution may be due; and they also contain finely divided and colloidal organic matter which is known to aid in the reduction of some minerals and the production of others that may be more easily dissolved. It is known that peat solutions are effective solvents of iron and silica,[48] and waters which are high in organic matter may also be high in iron and silica. This seems to be due to the solvent action of organic colloids and acids and to the presence of protective organic colloids. Malic, citric, acetic, and other acids of fruits and plants are annually produced in large quantities, and they must play a considerable part in rock decay and solution. Whitney[49] lists thirty-five organic compounds which have been identified in soils, but the extent to which these may influence rock decomposition is not known.

Other gases besides oxygen and carbon dioxide corrode rocks, but the important occurrences are more or less limited. Some volcanoes expel considerable quantities of hydrochloric acid, and this ultimately will be washed out of the atmosphere on to the earth with greater or less effects on the rocks with which it comes in contact. Sulphur gases also are expelled by volcanoes, result from the decomposition of sulphides, and are waste

[45] Campbell, M. R., Bull. Geol. Soc. Am., vol. 8, 1899, p. 221; Julien, A. A., Am. Assoc. Adv. Sci., vol. 28, 1879, p. 311; Bolton, H. C., Ann. New York Acad. Sci., vol. 1, 1877, p. 1, vol. 2, 1880, p. 1; Murray, A. N., and Love, W. W., Action of organic acids on limestone, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 1462–1475.

[46] Endell, K., Neues Jahrb., Beil.-Bd. 31, 1910, p. 1; Jour. Prakt. Chemie, vol. 82, 1910, p. 414. See also Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 487.

[47] Thayson, A. C., and Bunker, H. J., Microbiology of cellulose, hemicelluloses, pectin, and gums, 1927, pp. 161, 177. Book cites Stormer, Kayser, and Deleval as authorities. See also Harrar, N. J., Solvent effects of certain organic acids upon oxides of iron, Econ. Geol., vol. 24, 1929, pp. 50–61.

[48] Gruner, J. W., Origin of the sedimentary iron formations, Econ. Geol., vol. 17, 1922, p. 435; Moore, E. S., and Maynard, J. E., Solution, transportation and precipitation of iron and silica, Ibid., vol. 24, 1929, pp. 272–303.

[49] Whitney, M., Fundamental principles established by recent soil investigations, Science, vol. 54, 1921, pp. 348–351.

products of some industries, and their effects are of considerable local importance.

The soil mantle within a limited zone near the surface is thoroughly penetrated by small rootlets of plants, and in some way these act upon the substances of the rocks and place them in a condition to be absorbed. The ash of plants shows the large quantity and varied character of the material absorbed, but it is generally considered that the plants have obtained this material from soluble components of the soils and not directly from rocks. The experiment of growing a plant on a marble slab to obtain the root pattern shows direct action on a soluble rock, but the extent to which more resistant rocks will yield to plant roots is not well known. Such work as has been done indicates that the rock is attacked largely, if not wholly, by carbon dioxide secreted by the plant rootlets,[50] but it is possible that other substances are secreted of which the corrosive effects are greater than those of carbon dioxide.

Algæ, lichens, and mosses play some rôle in rock decomposition, but here quantitative data are scanty. Ash of lichens contains substances apparently derived from the rocks on which they lived.[51] Certain algæ are known to bore into the rocks, and limestone areas in the states of Kansas, Oklahoma, Montana, Wyoming, and elsewhere have the rocks more or less thickly covered with tiny algæ dwelling in depressions with diameters ranging from 0.2 to 0.6 mm. and with depths ranging from 0.1 to 0.2 mm. How rapidly these organisms work, the means by which they develop the depressions, and the products they make do not seem to have been determined. Bacteria also have been demonstrated to have some part in rock decomposition.[52] It is known that they reduce sulphates, and Logan[53] suggested that bacteria have been instrumental in the formation of an Indiana kaolin deposit; his conception of the stages occurring in the formation of the kaolin has, however, been criticised to some extent by Bucher.[54] Experiments made by Thiel[55] have proved that decomposition and solution of rocks are increased if soil bacteria are present in the waters flowing over them. In one set of experiments, he subjected hornblende-biotite granite, hornblende syenite, monzonite, quartz diorite, diabasic gabbro, Decorah shale, and ferruginous chert to the leaching of sterile waters, and in another set of experiments to

[50] Cameron, F. K., and Bell, J. M., Bull. 30, Bureau of Soils, U. S. Dept. Agric., 1905, p. 41.

[51] Jahresb. Chemie, 1847–1848, p. 1074. Cited by Clarke, F. W., op. cit., p. 487.

[52] Müntz, A., Ann. Chim. Phys., vol. 11, 1887, See Clarke, F. W., op. cit., p. 488.

[53] Logan, W. N., Kaolin of Indiana, Pub. no. 6, Dept. Conservation, State of Indiana 1919, pp. 45–76.

[54] Bucher, W. H., Econ. Geol., vol. 16, 1921, pp. 481–492.

[55] Thiel, G. A., The effectiveness of bacteria as agents of chemical denudation, Jour Geol., vol. 35, 1927, pp. 647–652.

waters containing soil bacteria. The greater decomposition and solution were produced by the waters containing the soil bacteria, the increase in lime and soda being marked and the total percentage increase of dissolved materials in the soil bacteria waters as compared with the sterile being 53. Thiel suggested that the results arose largely from CO_2 generation by the bacteria and not from their direct action on the rocks. Too little is known of the work of bacteria in rock decomposition, and it remains to be determined whether their presence in rocks may not in many instances be an effect and not a cause of decomposition.[56] As previously noted, it has been suggested that laterization may be the work of micro-organisms.[57]

The products arising from the decomposition of one mineral may aid in the alteration of adjacent minerals. Thus, alkaline carbonates increase the solvent ability of water for silica,[58] and the decomposition of pyrite, marcasite, and other sulphides may produce sulphuric acid whose presence may strongly affect neighboring materials.

Depth of Decomposition. Under the discussion of rock disintegration it was noted that the effects are largely confined to a thin zone near the surface and that the process is favored by the absence of a vegetable cover. Rock decomposition, on the other hand, is favored by a vegetable cover and may take place to the lowest limits of underground water circulation. In the District of Columbia[59] granitic rocks have been sufficiently decayed to a depth of 80 feet to be removable with pick and shovel; rock near Atlanta, Georgia, is locally decayed to a depth of 95 feet;[60] and in northwestern Georgia the depth of decay of limestones extends to 200 feet. In Brazil[61] shales have been altered to a depth of 394 feet, and in the Transvaal the granite of the Dakaap gold fields is decomposed to the depth of 200 feet.[62] It is suggested that most of the alteration occurs above the water table and extends but a short distance below its lowest position. Thus, regions with considerable relief would have the water table some distance from the surface and decomposition correspondingly deep, whereas humid regions of low relief would have the water table close to the surface and depth of decomposition slight. Decomposition might extend to great depths in arid and semi-arid regions because of the long distance the water table tends to be from the surface and thus decomposition would be far in advance of dis-

[56] Branner, J. C., Am. Jour. Sci., vol. 3, 1897, p. 438.

[57] Holland, T. H., On the constitution, origin, and dehydration of laterite, Geol. Mag., vol. 40, 1903, pp. 49–69.

[58] Hilgard, E. W., Am. Jour. Sci., vol. 2, 1896, p. 100.

[59] Merrill, G. P., Rocks, rock weathering and soils, 1906, p. 271.

[60] Spencer, J. W., Geol. Surv. Georgia, 1893, pp. 9–10.

[61] Derby, O. A., Am. Jour. Sci., vol. 27, 1884, p. 138.

[62] Furlong, W. H., Trans. Am. Inst. Min. Eng., vol. 18, 1890, p. 337.

integration so that most rocks would have experienced considerable decay before erosion brought them to the surface. The decomposition would proceed first along the structural planes between which the rock units would decay in the concentric fashion, known as spheroidal weathering, around the central part, the decayed portions exfoliating as conditions permitted. This is splendidly shown in figures 1 and 2. Most exfoliation seems to have decomposition as one of the causes and in many cases it is the most important cause.

FIG. 1. DIORITE SHOWING EXFOLIATION OR CONCENTRIC WEATHERING

Road-cut near Riverton. American River, Sierra Nevadas, California. Photograph by Eliot Blackwelder.

Consideration of the depth of decay in relation to the present water table may afford a valuable clue for the determination of the sequence of geologic events in a region, as both depth and rate of decay are related to the position of the water table. The latter is related to relief and this, in turn, to elevation above sea level. Thus, great depth of decay with a high water table suggests an earlier time when the water table stood lower. Barrell[63] has suggested that "beneath a typical peneplain there should be practically

[63] Barrell, J., Bull. Geol. Soc. Am., vol. 28, 1917, p. 760.

no ground water circulation," with the consequence that the mantle of decomposed materials should be thin and have fresh rock close to the surface. This has considerable significance in connection with unconformities.

Relative Importance of Rock Disintegration and Decomposition

It is difficult to state the relative importance of these two processes. It has been suggested that disintegration proceeds more rapidly in dry regions than in moist, in cold regions than in warm. What appears to have been meant is that the obvious products of regions of the characteristics first

FIG. 2. BOULDERS OF DECOMPOSITION DEVELOPING OUT OF JOINTED GRANODIORITE

The spheroidal weathering is beautifully shown. Two miles west of El Portal, Merced Canyon, Sierra Nevadas, California. Photograph by Eliot Blackwelder.

named in each case are more likely to be those of disintegration than decomposition, whereas in moist warm regions the obvious products are more likely to be those of decomposition. It is probable that disintegration is universal, that its effects differ little in different regions so long as like conditions of temperature range and cover prevail, except that in regions not subject to freezing, disintegration due to frost action is wanting and to that extent the process as a whole is lessened. In moist regions, whether warm or cold, decomposition continues the destruction, and the effects of disintegration are lost or masked. This is particularly true under the conditions of effective

vegetable cover, which retains the material in place until it is thoroughly decomposed. It does not follow, however, that the dominant products of dry regions are those of disintegration, as some dry regions have such deep underground water tables that complete decomposition of rocks extends far beneath the surface, so that the surface progressively is cut on decomposed materials. Products which are actually a consequence of disintegration may be referred to decomposition, when disintegration has reduced the rock to very small particles, as in the illustration given by Merrill[64] of an oligoclase in Delaware County, Pennsylvania, which seemed to be a kaolin-like substance, but which microscopic examination proved to be composed of particles resulting from disintegration.

As the two processes proceed more or less simultaneously, except under certain conditions, it follows that sediments in their early histories generally should be mixtures of particles derived from each. After the agents of transportation obtain the sediments, there tends to be a separation of the products of decomposition from those of disintegration, but the separation is rarely complete.

THE IMMEDIATE SOURCES OF TERRIGENOUS SEDIMENTS

The products resulting from rock destruction may at once be placed in transportation, so that the parent rocks are the immediate sources of the sediments, or the transportation may be deferred and the materials remain as residual soil for some time. Under average conditions it seems probable that the second possibility is the more common, and as the soil is known to be the locus of various chemical processes, organic and inorganic, more or less continuous changes in mineral composition are likely.

The mineral constituents of the soils fall into two groups: (1) common rock-forming minerals derived from the parent rocks, and (2) decomposition products derived from the first group. Minerals of the first group are in greater variety and in more complex mixture in the soils of greatest fineness,[65] unless decomposition is essentially complete, in which case there is approached a composition of which the chief constituents are quartz, hydrated aluminum silicates, and aluminum and iron hydroxides. Soils resulting from rock breaking will be largely composed of minerals of the first group (see table 5). The summary of Failyer, Smith, and Wade with respect to the constitution of soils is as follows:

> As a general rule the smaller particles of soils are richer in potassium, calcium, magnesium, and phosphorus than the coarser particles.

[64] Merrill, G. P., Rocks, rock weathering and soils, 1906, p. 227.

[65] Failyer, G. H., Smith, J. G., and Wade, H. R., The mineral composition of soil particles, Bull. 54, U. S. Bureau of Soils, 1908. p. 3.

The concentration of these elements in the finer components is the more pronounced as the soils have undergone extreme weathering.

In glacial soils and others resulting from mechanical processes the coarser particles are relatively high in the percentages of potash, lime, and magnesia.

The larger mechanical components contain these elements in forms which by protracted weathering will become more soluble, and they will ultimately be concentrated in the finer components.

Calcium is often rather low in clay soils resulting from the weathering of hard, compact limestones. It is generally abundant in soils recently formed from easily broken down limestones. The sands of these latter soils may contain a high percentage of calcium, probably as lime sand or as coatings on other large mineral grains.[66]

TABLE 5

ESSENTIAL CONSTITUENTS OF SOILS*

CONSTITUENTS	(1) 3 OHIO VALLEY ALLUVIAL SOILS	(2) 21 QUATERNARY LOESS SOILS	(3) 9 BLACK SLATE SOILS	(4) 32 TRENTON LIMESTONE SOILS
	per cent	*per cent*	*per cent*	*per cent*
Sand and insoluble silicates	84.310	88.098	80.131	73.380
Alumina, iron, and manganese oxides	9.835	6.941	10.587	11.200
Carbonate of lime	0.102	0.370	0.475	0.749
Magnesia (MgO)	0.189	0.292	0.524	0.644
Phosphoric acid (P_2O_5)	0.118	0.118	0.234	0.328
Potash in acid extract	0.450	0.257	0.178	0.404
Potash in insoluble silicates	1.405	1.706	N.E.	N.E.
Organic and volatile matter	3.472	2.937	5.929	6.211
	99.881	100.719	98.058	92.916

* Merrill, G. P., op. cit., p. 351.

A comparison of soils and soil-separates with crystalline rocks indicates that in the process of the weathering of these rocks the phosphate remains in about the same proportion or slightly increases. The lime and potash seem to decrease in percentage, although minerals containing these elements are always present.[67]

The rarer substances are not shown in table 5, as they commonly are in quantities too small for quantitative determination, but traces of many other substances; barium,[68] strontium, chromium, etc., usually are present.

[66] Failyer, Smith, and Wade, op. cit., p. 3.
[67] Failyer, Smith, and Wade, op. cit., pp. 35–36.
[68] Failyer, G. H., Barium in soil, Bull. 72, U. S. Bureau of Soils, 1910.

The common minerals of soils are given in the following list:[69]

Quartz	Biotite	Dolomite
Orthoclase	Olivine	Gypsum
Plagioclase	Serpentine	Talc
Hornblende	Epidote	Hematite
Augite	Apatite	Siderite
Muscovite	Zircon	Limonite
	Chlorite	Kaolinite
	Calcite	Zeolites (complex hydrated aluminum silicates of Ca, K, and Na)

In addition to the above, which may be considered basic substances, the following additional minerals, apparently mostly secondary products, have been identified:[70]

Apthitalite $(KNa)_2SO_4$	Mirabilite $Na_2SO_4 \cdot 10H_2O$
Aragonite $CaCO_3$	Natriolite $Na_2Al_2Si_3O_{10} \cdot 2H_2O$
Blodite $MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$	Northupite $MgCO_3 \cdot Na_2CO_3 \cdot NaCl$
Borax $Na_2B_4O_7 \cdot 10H_2O$	Picromerite $MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$
Carnalite $KMgCl \cdot 6H_2O$	Soda niter $NaNO_3$
Epsomite $MgSO_4$	Soda carbonate Na_2CO_3
Gaylussite $CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$	Sulphohalite $3Na_2SO_4 \cdot 2NaCl$
Halite NaCl	Sylvite KCl
Hanksite $9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$	Thenardite Na_2SO_4
Kieserite $MgSO_4 \cdot H_2O$	Thermonitrite $Na_2CO_3 \cdot H_2O$
Langbeinite $K_2Mg_2(SO_4)_3$	Tri-sodium phosphate
Leonite $MgSO_4 \cdot K_2SO_4 \cdot 4H_2O$	Trona $Na_2CO_3 \cdot HNaCO_3 \cdot 2H_2O$
Loewite $MgSO_4 \cdot Na_2SO_4 \cdot 2\frac{1}{2}H_2O$	Vanthoffite $MgSO_4 \cdot 3NaSO_4$
Magnesite $MgCO_3$	

These minerals are not of equal quantitative importance. Quartz, kaolin, and the iron oxides and hydroxides probably make up the largest part of most soils. Many of the substances given in the first list and most of those of the second are rare. In addition to the substances listed original plant and animal tissues are present, and Whitney[71] gives thirty-five organic compounds which have been isolated in soils, these compounds constituting the so-called humus. Many of these are listed as acids and most are of complex composition. They may be grouped in four divisions: (1) those containing carbon and hydrogen; (2) those containing carbon, hydrogen, and oxygen; (3) those containing carbon, hydrogen, and nitrogen, or those

[69] Lyon, T. L., Fippin, E. O., and Buckman, H. O., Soils, their properties and management, 1915, p. 9.

[70] Whitney, M., Science, vol. 54, 1921, pp. 348–351.

[71] Whitney, M., op. cit., p. 349. See also Schreiner, O., and Shorey, E. C., The isolation of harmful organic substances from soils, Bull. 53, U. S. Bureau of Soils, 1909; and Lyon, Fippin, and Buckman, op. cit., pp. 134–135.

containing carbon, hydrogen, oxygen, and nitrogen; and (4) those containing sulphur in addition to the elements named.[72] The quantity of the "humus" compounds generally appears to be small, but in the very peaty soils it may be large. A part of the humus content of soils consists of colloids with high adsorption for "water, gases, and such materials as calcium, magnesium and potash."[73]

TABLE 6

ORGANIC CONTENT OF UNITED STATES SOILS

	SANDY SOILS		CLAY LOAMS AND LOAMS	
	SOIL	SUBSOIL	SOIL	SUBSOIL
	per cent	*per cent*	*per cent*	*per cent*
North Central States	1.84	0.76	3.06	1.07
Northeastern States	1.66	0.66	3.73	1.35
South Central States	1.16	0.55	1.80	0.65
Southeastern States	0.93	0.41	1.53	0.73
Semi-arid states	0.99	0.62	2.64	1.11
Arid states	0.89	0.64	1.05	0.62

TABLE 7

HUMUS OF ARID AND HUMID SOILS

	PER CENT
41 arid upland soils	0.91
15 subirrigated arid soils	1.06
24 humid soils	4.58

The original organic matter in soils consists of plant tissue, parts of insects and other animals, charcoal, lignite, coal particles, and materials resembling bitumin and asphalt.[74]

The organic content of various soils and the decrease in organic content with depth are shown in table 6.[75] The percentages and variations of the humus content of soils under different conditions are shown in table 7.[76]

A third component of the soil is inorganic colloidal matter which Whitney[77] designates "ultra clay." This appears to be mainly composed of silica, alumina, iron oxide, and water, with small quantities of lime, magnesia, potash, soda, phosphorus, manganese, sulphur, and chlorine. The

[72] Lyon, Fippin, and Buckman, op. cit., p. 135.

[73] Whitney, M., op. cit., p. 350; Lyon, Fippin, and Buckman, op. cit., pp. 161–162.

[74] Schreiner, O., and Brown, B. E., Occurrence and nature of carbonized material in soils, Bull. 90, U. S. Bureau of Soils, 1912.

[75] Lyon, Fippin, and Buckman, op. cit., pp. 146–147.

[76] Hilgard, E. W., Soils, 1911, pp. 136–137.

[77] Whitney, M., op. cit., p. 350.

sum of the lime, magnesia, potash, and soda generally is low when the silica is low, and high when the silica is high. Silica and alumina generally vary inversely.[78] The silica appears to range from about 30 to more than 50 per cent. The colloidal matter gives hardness to the soil when it is dry, and plasticity when it is wet, and is an additional medium for the adsorption of gases and organic and mineral matter. It occurs as a coating on the larger grains of the soil and in aggregates.[79] According to Bouyoucos,[80] "the colloidal content of average soils is very high; in the sandy loams it may be as high as 20 per cent, loams 30 per cent, clay loams 50 per cent, and clay 75 per cent."

From the foregoing it is obvious that terrigenous sediments will vary in terms of the original rocks, the method of rock destruction, the age and origin of the soils resulting from the destruction of these original rocks, and the organic components of the soils. With so many variables there is the probability of a wide variation in the characteristics of the materials ultimately deposited.

Sediments of Organic Origin

Organisms produce sediments in the development of their protective and supporting structures, as bones, shells, and woody materials; and their activities lead to the deposition of such substances as phosphates, iron oxides, sulphur and sulphides, lime carbonate, etc. The protective and supporting structures relate only indirectly to rock destruction, and considerable parts of these structures are derived from water and air. The kinds of solid materials in the shells, tests, bones, and other structures of organisms which may form solid parts of the sediments are given in the list which follows.[81]

Solid materials contained in organisms

1. Protozoa	Foraminifera	Calcite Chitin*
	Radiolaria	Opal Acanthin*
2. Sponges		Calcite or aragonite Opal Spongin*

[78] Robinson, W. O., and Holmes, R. S., The chemical composition of soil colloids, Bull. 1311, U. S. Dept. Agric., 1924, p. 38.

[79] Davis, R. O. C., Constituents of soil material as related to sedimentation, Rept. Comm. Sedimentation, Nat. Research Council, 1924, p. 43. Terzaghi, C., Tech. Engineering News, vol. 9, 1928, p. 11, refers plasticity to the presence of scale-like particles.

[80] Bouyoucos, G. J., A rapid method for mechanical analysis of soils, Science, vol. 65, 1927, pp. 549–551.

[81] Modified after Blackwelder, E., manuscript.

3. Cœlenterates	Graptolites	Seracin?*
	Corals	Aragonite and calcite
4. Annelids		Calcite, phosphates, chitin*
5. Molluscoidea	Bryozoans	$CaCO_3$ Chitin*
	Brachiopods	Aragonite and calcite Chitin?* Dahllite
6. Mollusks		Aragonite and calcite, phosphate Chitin*
7. Echinoderms		Calcite
8. Arthropods	Crustacea	$CaCO_3$ (Calcite) Chitin*
	Insects, etc.	Chitin*
9. Vertebrates		Phosphate of lime, carbonate of lime, phosphate of magnesia, carbonate and chloride of soda, collophane, keratin, etc.
10. Plants	Diatoms	Opal
	Bacteria	$CaCO_3$, Fe_2O_3, S and other substances precipitated; not hard parts of organisms.
	Algæ	Calcite, aragonite, carbonate of magnesia.
	Mosses Ferns and lycopods Gymnosperms Flowering plants	Resins, waxes, and gums Cellulose

* Nitrogenous carbon compounds.

In addition to the substances listed above, it is known that magnesium carbonate, aluminum oxide, and sodium carbonate are present in the shells of many organisms, and calcium sulphate occasionally occurs.[82] The decay

[82] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates, Prof. Paper 102, U. S. Geol. Surv., 1917.

of organic matter may reduce some of the associated sediments, with concomitant formation of various substances, which in their turn may react with neighboring materials to form other compounds. The calcium and magnesium constituents form some of the limestones, and the opal of the diatoms, radiolaria, and sponges probably forms some of the flints and cherts.

Under certain conditions, plant matter accumulates to form deposits of great local importance. On the land this takes place in swamps, which in certain climates may be over much of the surface, or are associated with lakes, streams, and the sea. The bottoms of many lakes are black with partially rotten plant débris, and in parts of the sea there is a very large

TABLE 8

	VALLISNERIA	POTAMOGETON
	per cent	*per cent*
SiO_2	5.45	0.78
Fe_2O_3	0.81	0.11
Al_2O_3	0.57	0.23
Mn_3O_4	0.52	0.08
CaO	8.16	3.38
MgO	1.87	1.38
Na_2O	0.81	0.26
K_2O	5.48	2.08
Cl	1.32	0.56
S	0.85	0.82
P	0.23	0.13

annual production of plant matter. In the Danish waters it is stated that about 2300 square miles are covered with *Zostera* and that the annual production over this area consists of over 17,000,000 pounds of dry matter, or nearly 4 tons per square mile.[83] Lake Mendota at Madison, Wisconsin, with an area of 10,400,000 square meters, annually produces from its larger aquatic plants 2,203,000 kilograms dry weight of plant matter.[84] *Potamogeton* is responsible for 736,000 kilograms, and *Vallisneria* for 1,112,000 kilograms, the former containing 11.42 per cent ash and the latter 25.18 per cent, both analyses on a sand-free basis.[85] The composition of the ash

[83] Petersen, C. G. J., The sea-bottom and its production of fish-food, Rept. Danish Biol. Station to the Board of Agric., 1918, pp. 7–8.

[84] Rickett, H. W., A quantitative study of the larger aquatic plants of Lake Mendota, Trans. Wisconsin Acad. Sci., etc., vol. 20, 1921, pp. 501–507.

[85] Schuette, H. A., and Hoffman, A. E., Trans. Wisconsin Acad. Sci., etc., vol. 23, 1927, pp. 249–254.

is interesting in view of the large content of potassium oxide. The analyses of the inorganic constituents are given in table 8. The decomposition of the carbonaceous matter would yield a sediment high in lime, potash, and silica.

Each variety of organic matter may be segregated and form a deposit composed mostly of itself, but more commonly several are intermingled, and much more commonly several varieties are intermingled with sediments of other origins.

Sediments of Volcanic Origin

Sediments of volcanic origin are the so-called ash and larger fragments known as cinders, lapilli, bombs, etc. The ash is widely distributed, and it is thought that there have been many eruptions from which ash has made the circuit of the globe. Ash is found in many deposits, and thick beds are known to occur in regions remote from volcanoes, for example, the ash beds in the Tertiary of Kansas and Nebraska and the bentonite of the Cretaceous, Ordovician, and other strata. It possibly has wider distribution than any other form of sediment. Cinders, or lapilli, usually remain rather close to sources and ordinarily are not common in deposits remote from volcanoes, but if porous cinders or pumice fall upon water, they may be transported long distances and thus become incorporated with various other sediments. Exemplification of this fact is shown by slag occurring on many parts of the shores of Lake Michigan, though produced in the smelters in Gary, Indiana. Pumice, volcanic glass, cinders, and ash are among the most important of the inorganic components of deep-sea deposits.[86]

The quantity of volcanic sediments produced at certain times of earth history is known to have been very large. Capps[87] estimates that from an eruption occurring in the upper Yukon Basin 1000 to 2000 years ago a minimum of around 10 cubic miles of ash was ejected over a minimum area of 140,000 square miles. Martin[88] has collected data relating to other eruptions. Katmai in June, 1912, is estimated to have ejected 5 cubic miles of ash, and Krakatoa in 1883 ejected a quantity fully as large, although much of the latter probably was rock dust derived from older rocks. The eruption in 1815 of Tomboro on an island east of Java is estimated to have ejected between 26.6 and 50 cubic miles of material. The quantity of bentonite in the Cretaceous rocks of the Great Plains of the United States

[86] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, 1906, p. 381.

[87] Capps, S. R. Jr., An ancient volcanic eruption in the upper Yukon Basin, Prof. Paper 95, U. S. Geol. Surv., 1915, pp. 59–64.

[88] Martin, G. C., The recent eruption of Katmai volcano in Alaska, Nat. Geog. Mag., vol. 24, 1913, pp. 131–180.

and Canada has not been estimated, but it must have a magnitude of many cubic miles.

Volcanic ash is largely composed of glass in which are fragments and entire crystals of minerals of kinds resulting from the solidification of lava. The mechanical composition of the ash described by Capps is shown by a sample collected 420 miles from the inferred probable site of the vent of eruption.

	per cent
Caught on 0.423 mm. screen	7.72
Caught on 0.317 mm. screen	2.46
Caught on 0.254 mm. screen	4.78
Caught on 0.127 mm. screen	11.28
Passed 0.127 mm. screen	72.94

The fractions caught on the two coarsest screens contained considerable vegetable matter and sand.

Sediments of Magmatic Origin

To what extent matter is contributed by magmas more or less directly to sediments cannot be stated. It is pretty generally agreed that large quantities of highly heated liquids, mainly water, are given off by magmas, and that these liquids may carry many substances in solution. It has been suggested that the liquids may reach the surface as hot springs and there yield their burdens of dissolved and possibly suspended matter to surface waters.[89] The problem is further considered in connection with siliceous and iron-bearing sediments.

Sediments of Cosmic Origin

Deep-sea sediments contain small particles which have been referred to a cosmic or meteoric origin. Cosmic particles fall over the entire earth, but where the deposition of sediments is rapid their presence is masked by their relative fewness. On an exposed surface they soon disappear through decomposition. It is estimated that 15 to 20 million daily enter the atmosphere, about one to each 10 to 13 square miles. The annual contribution to the earth's mass from this source has been estimated at 5,000 to 7,000 tons, a quantity sufficient to make a deposit on the sea bottom of 1 foot in about 50,000,000,000 years.[90]

[89] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior Region, Mon. 52, U. S. Geol. Surv., 1911, pp. 506–516; Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. California Publ., Bull. Dept. Geol., vol. 11, 1918, pp. 402–408.

[90] Chamberlin and Salisbury, op. cit., pp. 381–382.

Summary

It has been shown that there are four and possibly five sources of sediments: (1) terrigenous matter, or that derived from rock destruction, (2) matter of organic production; (3) volcanic materials; (4) matter from magmas; and (5) cosmic dust. Of these sources the first named has the greatest quantitative importance, whereas the least contributions to sediments are thought to be those from magmas and cosmic sources. Terrigenous sediments are rock fragments of the same composition as the rocks from which they were derived, mineral particles from these rocks, and derived decomposition products, the last mainly quartz, hydrous aluminum silicates, aluminum and iron oxides and hydroxides, and carbonates. The complexity of the mineral mixture increases with limitation of decomposition and prolongation of disintegration and transportation; prolonged decomposition reduces the complexity of the mineral mixture.

The products resulting from the destruction of igneous rocks approximate 82 per cent shales, 12 per cent sandstones, and 6 per cent limestones. The complete decomposition of an igneous rock involves the addition of matter from the atmosphere and hydrosphere, which for 100 grams of the average igneous rock yields 107.4 grams of sediments in the proportion of 87.8 grams of average shale, 12.9 grams of average sandstone, 6.7 grams average limestone, and 6.6 grams of sea salts, much of which last will ultimately be deposited. In terms of volume, 100 units of volume of average igneous rock yield 111 units of volume of sediments exclusive of salts of the sea. The minerals of the igneous rocks undergo changes approximately as follows. The quartz increases from the 20.4 per cent in the average igneous rock to the 37.4 per cent estimated for the average sediment, the increase arising largely from the decomposition of the feldspars. This quartz is transported to the sites of deposition as macroscopic fragments, fragments of microscopic and colloidal dimensions, and in solution. The feldspars on complete decomposition yield silica, aluminum hydrates and hydrous silicates, white mica, various carbonates, and occasionally a few other salts. Some feldspar escapes decomposition and is transported and deposited as such, the quantity ranging from around 50 per cent in some arkoses to almost nothing in some sandstones and limestones.

The ferromagnesian minerals yield readily to decomposition, forming oxides, carbonates, and hydrates. Under certain climatic and topographical conditions some ferromagnesian minerals escape destruction and reach the sites of deposition essentially unaltered. If the enclosing sediments are of low permeability and are rapidly buried, these minerals may not decompose further and thus persist. The chances for this, however, are not excellent.

Of the common accessory minerals, magnetite and ilmenite resist decomposition fairly well and thus may reach the sites of deposition little changed. Apatite is fairly resistant and may attain deposition without alteration. Titanite readily alters to other minerals, as ilmenite, rutile, or leucoxene; but it may persist unchanged. Zircon is extremely resistant; mechanical transportation brings it to the sites of deposition, and it persists in the sediments chemically unaltered.

The various oxides of the average igneous rocks have entered into the sediments as follows:[91] 83 per cent of the silica transported becomes a part of the shales, 16.5 per cent enters the sandstones, and 5 per cent the limestones; 95.3 per cent of the total alumina may be expected to appear in the shales, 4.3 per cent in the sandstones, and 0.4 per cent in the limestones. Of the iron in the average igneous rock, 96.5 per cent may be expected to appear in the shales, 2.9 per cent in the sandstones, and 0.6 per cent in the limestones. Of the magnesia, 76 per cent will appear in the shales, 5.3 per cent in the sandstones, and 18.7 per cent in the limestones. The quantity of magnesia in the average sediment, however, fails to account for the quantity in the average igneous rock. On the other hand, the average sedimentary rock shows an excess of lime. The deep-sea deposits may account for these discrepancies. Of the lime, 43.6 per cent enters the shales, 45.2 per cent the limestones, and 11.2 per cent the sandstones. Soda occurs in the sediments with 95 per cent in the shales, 4.7 per cent in the sandstones, and 0.3 per cent in the limestones. The quantity of it released by the average igneous rock is much greater than that in the average sedimentary rock, the discrepancy probably arising from the quantity of sodium in the sea. It also may be in part explained by the fact that the sedimentary rocks analyzed have been mainly derived from sources close to the surface and thus have lost a part of their sodium. The potash tends to remain with the clay, 93.8 per cent being found therein, with 5.5 per cent in the limestone, and 0.7 per cent in the sandstones. Analyses of rocks from deep beneath the surface might show a greater per cent of potash in the limestones and sandstones.[92]

In the destruction of the average igneous rock it does not follow that the products of destruction will be distributed as they exist in the average sediments.

Sandstones and quartzites, to the extent that they are composed of quartz sands, break up into grains of the same material, the grains in many, and perhaps most, instances, being those originally deposited. These may

[91] Based on existing contents of sediments.

[92] Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 63, 64, 69, 76, 78, 79, 81–88.

attain the sites of deposition with no change other than reduction in volume. In so far as a sand rock is composed of minerals other than quartz, the products resulting from destruction will contain these substances or products of their decomposition.

The clay group of rocks contains hydrous silicates, some silicates derived from previous rocks, small fragments of quartz, some iron and aluminum oxides and hydroxides, and other substances in small percentages. The original silicates may remain unchanged or yield decomposition products. The iron compounds are likely to be in both ferrous and ferric forms, and these yield iron hydroxides and oxides unless much organic matter is present, in which case iron carbonate may result. Some of the hydrous silicates may decompose to form oxides and carbonates.

Limestones and dolomites destroyed by mechanical processes yield fragments of these rocks. If climatic conditions are favorable, the carbonates pass off in solution, leaving a residue of hydrous aluminum silicates, iron and aluminum oxides and hydroxides, and chert, the quantity of the last in some instances being extremely large.

Rock salt, gypsum, and similar substances usually pass into solution, leaving little residue.

Chert is extremely resistant and enters the sediments in relatively large pieces. Under certain conditions some of the silica passes into solution, and the rock becomes porous or powdery, the color ranging from white to red.

All forms of rock destruction yield more or less sedimentary material of colloidal dimensions. The quantity is unknown and it may be large.

In the katamorphism of igneous rocks a certain quantity of the stable and moderately stable minerals escapes destruction and becomes part of the sedimentary rocks. The destruction of these sedimentary rocks in turn results in elimination of the less stable minerals which had passed through the first sedimentary cycle, so that the rocks resulting from the aggregation of products arising from the destruction of sedimentary rocks will contain a lesser variety of stable and relatively stable minerals than the parent rocks. This process of elimination continues with each sedimentary cycle, with the result that sedimentary rocks which have behind them a great number of sedimentary cycles[93] are characterized by a limited quantity of very stable minerals of igneous ancestry.

To relate the derived minerals of sedimentary rocks of a given region to

[93] Sedimentary cycle, as here used, represents that portion of the metamorphic cycle extending from the destruction of a parent rock to the aggregation of the particles of destruction to form a sedimentary rock. It should not be confused with the term "cycle of sedimentation" used on later pages.

their parent rocks (provenance) requires a knowledge of the mineral constitution of the earlier rocks of that and adjacent regions, particularly of those crystalline rocks which might be the ultimate parents. A corollary to this statement is that knowledge of the mineral constitution of crystalline rocks is an essential pre-requisite of the problem.

CHAPTER II

THE TRANSPORTATION, DEPOSITION, DIAGENESIS, AND LITHIFICATION OF SEDIMENTS

The Transportation and Deposition of Sediments

The separation of fragments from the solid rock is the beginning of transportation, and its duration may range from this short interval of time to millions of years, some of the material in solution in the sea probably having been there since the first occurrence of water. The duration of transportation has considerable influence on the character of the sediments which may be deposited, as both mechanical and chemical change may continue throughout. Under some methods of transportation a sorting of the sediments occurs, the perfection of which depends on the duration and character of transportation. Sediments which undergo long transportation may ultimately result in a single substance being deposited at any one place. Long transportation of fine, stable materials suggests greater mineral variety.

Transportation may be accomplished by water, atmosphere, ice, action of gravity and changes of temperature, and organisms. In the case of any sediment it is very probable that several methods of transportation intervene between its origin and deposition. Of the five methods of transportation those usually considered are water, atmosphere, and ice, the other methods being considered of less importance.

The deposition of sediments is so intimately interlocked with transportation that the two processes can with difficulty be separated in discussion, and they are therefore here considered together.

The materials transported and deposited range through wide dimensions, with every possible transition from the minimum to the maximum. Precision demands that their classification and the terms which express dimensions of particles should be on a mathematical basis. Several classifications have been proposed, but that of Wentworth,[1] given below, appears to be most in keeping with the requirements. The dimensions are in geometrical ratio, the ratio not being the same throughout.[2]

[1] Wentworth, C. K., Grade and class terms for clastic sediments, Jour. Geol., vol. 30, 1922, pp. 377–392.

[2] For other classifications, see: Grabau, A. W., Principles of stratigraphy, 1913, p. 287; Keilhack, K., Lehrbuch der praktischen Geologie, 2te. Auflage, 1908, pp. 527–528; Merrill, G. P., Mechanical analysis of residual sand of diabase and of washed kaolin, Bull.

	mm.
Boulder	256 or above
Cobble	64–256
Pebble	4–64
Granule	2–4
Very coarse sand grain	1–2
Coarse sand grain	$\frac{1}{2}$–1
Medium sand grain	$\frac{1}{4}$–$\frac{1}{2}$
Fine sand grain	$\frac{1}{8}$–$\frac{1}{4}$
Very fine sand grain	$\frac{1}{16}$–$\frac{1}{8}$
Silt particle	$\frac{1}{256}$–$\frac{1}{16}$
Clay particle	Smaller than $\frac{1}{256}$

TRANSPORTATION AND DEPOSITION BY WATER

Transportation and deposition by water are considerably different, depending on whether they are accomplished by rain wash, streams, or the waves and currents of standing bodies of water. For streams the movement is generally in a single direction; in bodies of standing water the movement frequently reverses direction.

Transportation by Rain Wash

Transportation by rain wash differs somewhat with climatic conditions. In regions of much rainfall the water may flow over the surface as sheets in heavy rains, and in moderate rains as a combination of sheets and small rills. As any surface has considerable small variations of slope, there are frequent changes from aggradation to degradation, and there may be a tendency for rain wash to develop a surface of uniform slope, the fine material moving downhill, the coarse material moving little, merely settling as the fine material is moved from around and beneath it.

In semi-arid climates the methods are different. During the dry periods, water is brought to the surface through capillary action, evaporation occurs, and if the material in solution is adequate, the surface may become cemented to a hard crust. Rain falling on this surface may not be greatly absorbed, and the flow does little erosion until a place is found where the crust can be penetrated and the underlying uncemented material attacked. This leads to the development of tiny cliffs over whose edges the water trickles as tiny streams. These erode channels of small dimension on the cliff faces, which ultimately take the appearance of having been scratched by claws.[3] In

150, U. S. Geol. Surv., 1898, pp. 380–383; Thoulet, J., Étude minéralogique d'un sable du Sahara, Bull. Société Minéralogique de France, t. IV, 1881, pp. 262–268; Baker, H. A., Investigation of the mechanical constitution of loose arenaceous sediments by the method of elutriation, Geol. Mag., vol. 57, 1920, pp. 321-322.

[3] Jutson, J. T., On the clawing action of rain in sub-arid Australia, Proc. Roy. Soc. Victoria, vol. 32, pt. i, 1919, pp. 20–21.

examples described by Jutson the heights of the cliffs ranged from 1 to 6 inches. Reaching the bases of the cliffs, the tiny rills form small fans or cones on which the water disintegrates into distributaries, which flow downward until a lower cliff is reached and the process is repeated. Due to undermining, the cliffs recede, and large blocks resting on the crust surmounting any cliff are undermined and roll down the slope for considerable distances. Under these conditions the surface of the slope becomes broken up into a series of miniature terraces and cliffs, with each cliff moving backward.

In arid regions where the surface materials remain loose and incoherent, these and the water may unite in such a way as to form a thick liquid which flows as a sheet to the foot of the slopes on which the materials lie.[4]

The sediments thus transported are deposited ultimately at the foot of the slope involved, together with the materials moved by creep, etc., forming that type of deposit known under the general name of *colluvium*.

Transportation and Deposition by Streams

SOURCES OF LOAD. The materials which streams transport are brought to them by ground water, rain wash, creep, landslides, wedge work of ice and roots, and expansion of materials in cliffs beyond the positions of stability. Animals, particularly man, dump vast quantities into many streams. Water animals stir up the bottom and thus assist in transportation. Considerable quantities of sediment drop into streams from the atmosphere, large proportions of which consist of leaves and other vegetable matter, and in some regions material of volcanic origin is contributed in large volumes. By their own efforts in undermining, abrasion, grinding, impact, and solution, streams obtain sediments from their banks and the bottoms of their channels. If they rise in a region of glaciers, great volumes are brought to them by the ice. The load carried by a stream may, thus, have many sources.

METHODS OF TRANSPORTATION BY WATER. Water transports materials by traction, suspension, and solution. The first and second methods are mechanical, the third is chemical.

Traction is intended to include those mechanical methods of transportation wherein the particles slide, roll, or make short jumps, the last being termed saltation.[5] Leaping particles are obviously in suspension. Motion frequently changes from rolling to sliding, or leaping, the latter being favored

[4] McGee, W. J., Sheet flood erosion, Bull. Geol. Soc. Am., vol. 8, 1897, pp. 87–112; Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 24, 1913, pp. 256–257.

[5] McGee, W. J., Bull. 19, U. S. Geol. Surv., 1908, p. 199.

by certain irregularities of the bottom. Under average conditions the very large particles roll or slide. Slab-shaped particles may turn over and over until the downstream end becomes higher than the upstream, when a condition of stability is attained, and the particles then shingle upstream. Slab-shaped particles also do considerable leaping when they are so inclined with respect to the currents that the force of the water is directed against their lower surfaces. Owens has noted that when a flat stone is thrown into a current it rolls "irregularly for a moment or so, and then gets up on its edges and rolls along like a wheel," and he concluded that this form of traction is the "normal method of travel of such flat disc-like stones when passing over a smooth hard bottom."[6] It is doubtful if the last conclusion can be sustained, but in the writer's experimental work such a mode of progression has been observed on laboratory stream tables in particles of low specific gravity and particles with large surface with respect to volume. Pebbles with prolate spheroidal shapes, or with one long dimension and two shorter, roll parallel to the longest axis and ultimately come to rest in that position, laboratory studies showing this rule to be almost universal. Furthermore, pebbles placed on a sand bottom in a current too weak to transport them, rotate through washing of sand beneath them until they attain a position with their longest axis perpendicular to the current, the median axis at the same time acquiring a position that dips up-current.[7]

The particles moved by traction may travel collectively. When the bed load is small, the sands on the bed develop into small "dunes" of asymmetrical profile and these gradually travel downstream, giving the "dune" phase of traction. Erosion takes place on the upstream side of the "dune," and deposition on the lee or downstream side. An increase in velocity or load causes the "dunes" to disappear and the surface of the bottom to become smooth, giving the smooth phase of traction in which the sand moves as a sheet over the entire bed. Both the "dune" and the smooth phases of traction under some conditions of stream velocity give rise to a form of traction wherein ridges develop that travel upstream through erosion on the downstream sides and deposition on the upstream sides. The slopes of these ridges, or "antidunes," as Gilbert designated them, are more symmetrical than those of the "dunes" and they travel upstream more rapidly than do the latter downstream.

The three types of traction appear to be functions of the depth, load, bed resistance, and velocity. Under certain relations of velocity, load, depth, and bed resistance, sinuosity of currents is reduced to a minimum, and the

[6] Owens, J. S., Experiments on the transporting power of sea currents, Geog. Jour., vol. 31, 1908, p. 418.

[7] Hunzicker, A., Unpublished thesis, Univ. Wisconsin, 1930.

smooth phase of traction results. Increase in depth without increase in velocity seems to produce diversity of current, giving the "dune" phase of traction. Increase in velocity without increase in depth gives the "antidune" phase,[8] but the formation of this feature seems to be favored by some irregularity of the bottom, such as change in slope. The development of "antidunes" dams the current and thus accumulates water which ultimately eliminates the "antidunes" and gives the smooth phase of traction.[8]

Suspension is that method of transportation wherein the particles are lifted above the bottom and floated for considerable periods of time. Suspension of the larger particles is largely dependent on velocity, but the smaller particles and those of colloidal dimensions remain in suspension for very long periods of time irrespective of the velocity, of which the latter is essentially independent. With lowering of velocity, the larger particles settle and become a part of the traction load. Upward currents resulting from the sinuous and swirling motion of the water are largely responsible for this method of transportation, and were these not present, the larger particles of the non-colloidal suspended load would rapidly settle.

The transportation and deposition of matter carried in solution are independent of velocity.

Transportation by traction and suspension of non-colloidal matter are considered more or less together, as it is difficult to separate the two processes, inasmuch as particles change from one to the other method of transportation with slight changes in the velocity of the water. All methods will first be considered as they apply to streams and subsequently for standing bodies of water.

Transportation by Traction and Suspension in Streams. Each stream "may be considered to be made up of a number of streams which are always changing places, ascending or descending, or moving from side to side, or spirally in whirls."[9] They may be divided into those with bed-rock banks and bottoms and those whose banks and beds consist of alluvium. As the former type has local distribution, transportation and deposition are considered only in relation to the latter.

All streams are more or less crooked, so that the line of greatest velocity impinges alternately on opposite sides of the channel, the swiftest current crossing the stream from one concave bank to another. In the straight reaches of a stream with symmetrical profile, the current is swiftest in the

[8] Gilbert, G. K., The transportation of débris by running water, Prof. Paper 86, U. S. Geol. Surv., 1914, pp. 31, 34, 243.

[9] Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 24, 1913, p. 256.

middle at some distance above bottom. At stream bends there seems to be something of rotary movement to the current, with the axis of rotation parallel to the stream direction, the surface waters flowing toward the concave, and the bottom waters toward the convex bank.[10] This rotation develops a greater diversity in both direction and velocity of the currents than obtains where such rotation does not occur, thus increasing transportation both by traction and suspension.

Bed and bank velocities in crooked streams are higher on the convex sides of the current and lower on the concave sides, a diversity favorable for traction and suspension, and also responsible for erosion of banks and beds on the convex sides and deposition on the concave sides.

Decrease in velocity of streams, in general, leads to a settling of the coarsest portions of the suspended load and a grounding of the coarsest portions of the tractional load, whereas increased velocity has the opposite effect; but large particles of the tractional load may come to rest later than smaller ones, due to their projecting above the slower currents in contact with the bottom, the larger particles thus coming to rest on smaller.

Streams usually vary greatly in their discharge, and discharge is one factor conditioning velocity. Discharge is most steady in plant-covered regions and least steady in semi-arid ones, in which the response of streams to rainfall is flashy, a channel changing in a few hours from a dry coulee to a raging torrent.

Streams consist of alternations of deeps and shoals, the former apt to be situated on the convex sides of the current, the latter where the currents cross to the opposite sides. During floods, bed velocities in the deeps become relatively high and diverse, traction and suspension are at the maximum, and more materials may be brought to the shoals than may then be transported therefrom. Poor sorting is probable. Floods thus mean erosion in the deeps and building on the shoals, part of which is in the form of bars, general facts well known to river pilots.[11] As flood waters subside, bed velocities decrease, and a time comes when deeps contribute nothing to the stream load. The places of deposition and erosion then interchange. The currents over the shoals bring nothing from the deeps, and some part of their energies is applied to bed erosion, and some of the material thus derived is deposited in the deep next below. Thus, a rising river erodes from its deeps and deposits on its shoals, whereas a falling river scours from the shoals to deposit in the deeps. The variation in depth of a deep between low and high water not uncommonly reaches considerable magnitude, Todd

[10] Gilbert, G. K., op. cit., p. 220.

[11] McMath, R. E., Rept. Mississippi River Comm. for 1881, p. 252; Gilbert, G. K., op. cit., p. 232.

having noted such a variation in the Missouri River in Nebraska of about 36 feet between July 28 and November 18, 1882.[12]

As the shoals are scoured, the finer materials of the upper portion are removed and the coarser are left, so that the deposit on the shoals consists of heterogeneous materials with coarse particles on top. During erosion of the deeps, fine materials are removed and coarse remain; during low water, the deeps are receiving deposits of fine material which come to rest on coarse. If deeps and shoals always maintained the same positions, no deposits other than those last made would result, but as they change positions more or less continuously, each tending to migrate laterally and also downstream, some deposits of each may become permanent.

The vertical distance separating the deposit on a shoal from that in a deep may be of considerable magnitude; in the example given for the Missouri River it must have been around 50 feet. There thus develop deposits which were formed at the same time and are only short horizontal distances from each other, yet one lies far above the other.

Kinds of material transported and deposited by stream traction and suspension. The materials of the tractional load of streams vary with velocities of the currents. They ordinarily consist of sands and larger particles, although low velocities transport fine materials in this way. The sands and smaller particles are largely quartz or some other resistant mineral. The larger particles may also be composed of quartz, but far more commonly they are rock fragments of a wide range of characteristics. Not infrequently considerable quantities of mica flakes appear to be transported by traction.

Materials transported in suspension range from fine sands to particles of almost infinite fineness. Streams flowing through regions of micaceous rocks carry considerable quantities of mica flakes, these usually being somewhat larger than the associated sand grains. Vegetable matter in timbered regions constitutes a considerable proportion of the load.[13] Some sedimentary particles are transported in foam, as may easily be shown by examination of the foam on most bodies of water. Dry and oil-covered mineral particles up to 2 mm. or more in diameter may be floated on the surface of water, being held up by the surface tension. This flotation is favored by a film of oil on the water. Hennessy has described the floating of hundreds of particles ranging "from the smallest visible to the eye up to small pebbles, nearly as broad and a little thicker than a four penny piece," the locality being on the west coast of Ireland, when they had been picked up by the

[12] Todd, J. E., Moraines of southeastern South Dakota, Bull. 158, U. S. Geol. Surv., 1899, p. 151.

[13] Kindle, E. M., Notes on sedimentation in the Mackenzie River Basin, Jour. Geol., vol. 26, 1918, p. 350, fig. 5, pp. 358–359, figs. 12–13.

rising tide and carried inland.[14] The top surfaces of the particles were dry.

Competency, capacity, and load. By *competency* is meant the ability of a stream to transport in terms of dimensions of particles. For a stream with a given discharge, flowing in a given channel and dealing with materials of a given character, there is a competent slope over which these materials may be transported. With decrease in slope, the load decreases. For a given slope in a given channel, with materials of a given character, there is a competent discharge, and for a given discharge in a given channel there is a competent fineness. It has been stated that the dimension of a particle which a stream is competent to transport varies as the sixth power of the velocity,[15] but Deacon[16] concluded that the variation is the fifth power of the velocity.

Streams are more competent to transport material after it has been brought into the currents, particularly after it has been lifted up above the slow bottom currents. It was noted by Owens that sedimentary particles which at a certain velocity are transported on a smooth stream bed, at the same velocity tend to remain stationary in the hollows of a rippled bottom. He further found that with a given velocity a particle is more readily moved when isolated than when it is associated with others of somewhat similar dimensions, as under the latter conditions each particle derives support from its neighbors.[17] This may be seen on any stream table where relatively large particles are transported over surfaces of loose sands, the latter remaining stationary. An aggregate, moreover, requires a higher velocity to move it than does a single object of the same mass.[18] Blackwell's experiments showed a velocity of 2.25 to 2.50 feet per second to be competent for the movement by traction of pebbles having a diameter of 12.56 mm., one of 1.25 to 1.50 feet per second for pebbles of half that dimension, and sand was moved at velocities of 1 foot per second. With higher velocities the competency and hence the dimensions of the particles increase. Blackwell's conclusions, as given by Gilbert, are that (1) the character remaining the same, competent velocity increases with the mass; (2) for objects of the same size and shape it increases with specific gravity; (3) the competent velocity for particles of the same shape is the greater as they depart from a

[14] Hennessy, H., On the flotation of sand in a tidal estuary, Geol. Mag., vol. 8, 1871, pp. 316–318. See also Verrill, A. E., Am. Jour. Sci., vol. 24, 1882, p. 449.

[15] Leslie, Sir John, Elements of natural philosophy, ed. of 1829, vol. 1, pp. 426–27. Quoted by Gilbert, G. K., op. cit., 1914, p. 16.

[16] Deacon, G. F., Proc. Inst. Civil Eng., vol. 98, 1894, pp. 93–96.

[17] Owens, J. S., op. cit., p. 418.

[18] Blackwell, T. E., Accounts and papers: (London) Sess. 2, 1857, Metropolitan drainage, vol. 36, appendix IV, pp. 167–170. Quoted and amplified by Gilbert, op. cit., p. 216.

sphere; and (4) "for objects in motion the rate of travel increases with the velocity of the current."

Experiments by Suchier[19] in the Rhine River at Breisbach gave the results which follow:

	m. per sec.
A. With stream bed covered by fine sediment.	
Under action of current alone, no movement found with bottom velocity at	0.694
After being stirred up, the movement of the sediment began for fragments of the size of a bean, when bottom velocity reached	0.897
Fragments of the size of hazelnuts, when bottom velocity reached	0.923
Fragments of the size of walnuts, when bottom velocity reached	1.062
Fragments of the size of a pigeon egg, when bottom velocity reached	1.123
B. With river bottom free from sediment.	
The smallest particles are moved when the current velocity reaches at bottom	1.180
Pebbles of pea and hazelnut size move freely with a velocity of	1.247
With noticeable noise at	1.300
Pebbles of walnut size are moved without stirring, and such of 250 grams weight after stirring up, with current at	1.476
Pebbles of 1000 grams weight rolled at	1.589
C. General movements of pebbles:	
Up to the size of pigeons' eggs, at	1.800
Up to the size of hens' eggs, at (including such of 1500 grams)	1.717
Pebbles of less than 2500 grams weight are moved at	1.800
All pebbles moved at	2.063

The following table shows that a much greater velocity is required to start motion than to continue it after once started.

TABLE 9

SIZE OF PEBBLES	VELOCITY REQUIRED TO MOVE AFTER STIRRING UP	VELOCITY REQUIRED TO START MOTION
	m. per sec.	m. per sec.
Hazelnut size	0.923	1.35
Walnut size	1.062	1.39
Pigeon egg size	1.123	1.45

Competency is extremely great in many mountain streams and in torrents occasioned by the breaking of dams. Prestwich records the moving over a distance of a third of a mile of a block of rock with weight of about

[19] Suchier, Die Bewegung der Geschiebe des Oberrhein, Deutsche Bauzeitung, No. 56, 1883, p. 331. Cited by Grabau, A. W., Principles of stratigraphy, 1913, pp. 250–251.

20 tons (dimensions 22 x 6 x $3\frac{1}{2}$ feet) in a flood caused by the breaking of a dam.[20] Blocks weighing several thousand tons were moved by the breaking of the Los Angeles St. Francis dam.

The competent velocity for the transportation of materials in suspension is greater than for the transportation of the same materials by traction.

By *capacity* is meant the maximum load a stream can carry. It depends on the slope of the stream; the discharge; the velocity, shape, size, and specific gravity of the materials transported; the ratio of depth of water to width of stream; and the degree of mixing of materials.[21] Some of these factors are dependent on each other. The steeper the slope, for example, the greater the capacity. For constant slope but variable discharge, the capacity varies on the average with the 3.2 power of the velocity. If discharge is constant, but slope and therefore velocity variable, capacity varies on the average with the fourth power of the velocity; and if the depth is constant, with slope and discharge variable, the variation in capacity averages about the 3.7 power of the velocity.[22] "Debris composed of single size is moved less freely than debris containing particles of many sizes," and in streams with smooth bottoms "for rolled particles the capacity increases with coarseness, for leaping particles with fineness," and it "is most sensitive to changes in the conditions which control it when near its lower limit."[23]

The capacity is greater in wide streams than in narrow, this probably being true because of the larger quantity of water in contact with the bed. The capacity is also increased for substances of low specific gravity and irregularity of shape, the irregularities increasing the surface and thus the resistance of particles to sinking. Aggregates composed of particles of a single size are moved less freely than aggregates containing particles of many sizes. Mixtures of fine and coarse materials increase the capacity for coarse materials.

The *load* of a stream is the actual quantity of material carried at any one time. The load increases the mass of the moving substance and thus the energy is increased; mechanical work is involved in its transportation, and this lowers the stream's energy, and further energy is lost by the stream in that the presence of the material makes it more immobile.[24] The net result appears to be that a load causes retardation. The loads of streams

[20] Prestwich, J., On some effects of the Holmfirth flood, Quart. Jour. Geol. Soc., vol. 8, 1852, pp. 225–230.

[21] Gilbert, G. K., Hydraulic mining débris in the Sierra Nevada, Prof. Paper 105, U. S. Geol. Surv., 1917, p. 26.

[22] Gilbert, G. K., Transportation of débris by running water, Prof. Paper 86, U. S. Geol. Surv., 1914, p. 11.

[23] Gilbert, G. K., op. cit. p. 26.

[24] Gilbert, G. K., op. cit., p. 11.

vary within wide limits, and few streams appear to be loaded to capacity. Arid and semi-arid regions and cultivated regions of considerable relief have streams carrying the largest loads, and this locally rises to percentages of 10 or more. The Rio Grande River has records showing a suspended load of 10 per cent by volume,[25] and near its mouth the Mississippi has an average load of 0.07 per cent[26] with a recorded maximum of 0.8 per cent.[27] Observations made on the Fraser River of British Columbia show that the maximum load is carried during the flood season, being greatest during the early part of that season, when it rose in late April and early May, 1920, to 230 parts of dried solid matter (dried at 180°C.) per million, whereas during the low-water season in February of the same year the load was as little as 10 parts per million.[28]

The relative proportions of materials transported by suspension and traction have been determined in few instances. The matter is difficult of determination, but the ratios for materials of different fineness might be of use in the interpretation of some deposits of the geologic column. Humphreys and Abbot give the tractional load at a bar across one of the mouths of the Mississippi as 11 per cent of the suspended load.[29] For the Rhone, Guérard[30] found that the suspended load was less than one-fourth of the whole. Gilbert's studies of the material transported by the Yuba River in California led to the conclusion that the suspended load was approximately equal to the tractional load.[31] These ratios are widely variant and suggest that velocity and supplies of materials for the two types of loads may be the most important factors in determining the ratio.

Quantity of material mechanically transported. The quantity of material transported by mechanical methods by the Mississippi River is given at 400,000,000 tons or 7,471,411,200 cubic feet per annum,[32] and Salisbury[33] estimates that all the rivers of the world carry about 40 times as much as the Mississippi, giving an approximate total of 16 billion tons of material carried by mechanical methods to the sea by all the streams of the world. The streams of the United States are estimated to carry a total of 513,000,-

[25] Stabler, H., Water Supply Paper 274, U. S. Geol. Surv., 1911, pp. 102–104.

[26] Humphreys, A. G., and Abbot, H. L., Physics and hydraulics of the Mississippi River, 1861 and 1867.

[27] Seddon, J. A., Rept. Chief Engineer, U. S. A., 1887, p. 3094.

[28] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv. Canada, 1921, p. 23.

[29] Humpheys and Abbot, op. cit., p. 149.

[30] Guérard, A., Min. Proc. Inst. Civ.-Eng., vol. 82, 1885, pp. 308–310.

[31] Gilbert, G. K., op. cit., 1914, p. 230; also Bull. Geol. Soc. Am., vol. 18, 1907, pp. 657–659.

[32] Humphreys and Abbot, op. cit., pp. 148–150.

[33] Salisbury, R. D., Physiography, 1907, p. 122.

000 tons to the sea annually.[34] If the quantity transported by the streams of the United States as dissolved and suspended matter could have been taken from the Panama Canal there "would have been excavated the prism for an 85-foot level canal in about seventy-three days."[35]

Effects of long hauls. Material which has undergone short transportation either by traction or suspension is as a rule very similar to the rocks from which it came. Long transportation by traction results in larger and smaller particles, of which the latter may have several composing minerals; the particles of sand dimension are usually quartz or garnet. Rounding is better developed after long than short hauls, although in waters with a heavy load of coarse suspended matter there is a great deal of rounding within short distances, this being particularly true with respect to waters coming from glaciers.[36]

Materials transported in suspension may increase in complexity with the distance of the haul, and the sediments at any place in a stream may contain components derived from every part of the region drained by this stream above the place where the sediments occur, and in addition there will be contributions from the atmosphere.

Transportation of Matter in the Colloidal State. The matter transported in the colloidal state is so finely divided that it does not settle through the influence of gravity, and unless flocculated or coagulated by electrolytes in solution or colloids of opposite sign, it tends to remain indefinitely in suspension. Colloidal matter is extremely common and constitutes a large percentage of some clays; is produced in rock decomposition; and results from rock abrasion, grinding, and impact. Colloidal matter has been produced by abrasion and grinding of quartz, feldspar, and other substances.[37] The colloids in clay are in the form of gels and consist of silicon dioxide, hydrated aluminum oxide, hydrated ferric oxide, and organic matter,[38] the last constituting some of the so-called humic acids. It seems probable, moreover, that the silicon dioxide indicated by analyses of the solid matter in solution in natural waters is really in the colloidal state and not in true solution.[39] The same comment may be made for the ferric and aluminum

[34] Dole, R. B., and Stabler, H., Denudation, Water Supply Paper 234, U. S. Geol. Surv., 1909, p. 83.

[35] Dole and Stabler, op. cit., p. 83.

[36] Chamberlin, Rollin T., Letter of November 20, 1921.

[37] Lenher, V., Silicic acid, Jour. Am. Chem. Soc., vol. 43, no. 3, 1921, pp. 391–392. Marshall, P., Colloid substances formed by abrasion, Trans. New Zealand Inst. vol. 59, 1928, pp. 609–613.

[38] Ashley, H. E., The colloid matter in clay and its measurement, Bull. 388, U. S. Geol. Surv., 1909, pp. 12, 59.

[39] Kahlenburg, L., and Lincoln, A. T., Solution of silicates of the alkalies, Jour. Phys. Chem., vol. 20, 1898, p. 90; Kohlrausch, F., Zeitschr. physical. Chemie, vol. 12, 1893, p. 773; Moore, E. S., and Maynard, J. E., Econ. Geol., vol. 24, 1929, pp. 296–302.

oxides, perhaps a part of the calcium carbonate, and possibly other substances.[40] Regions which have alkaline ground waters tend to lose large quantities of silica in "solution," while those which have acid waters lose oxides of iron and alumina.[41] In the former the iron and alumina are left behind to form laterite, and in the latter silica may be concentrated in the surface materials.

The colloidal matter carried by streams probably undergoes much flocculation and precipitation during the passage seaward, but on arrival at the sea essentially all of it is flocculated at the places of mingling of the fresh and salt waters. This may be a considerable distance seaward from the mouths of streams. After flocculation, large quantities may be carried seaward for long distances before deposition is accomplished, as the aggregates have such low densities that they may be carried in marine currents in spite of low competencies. At some places of deposition it is probable that considerable thicknesses of very fine material are deposited, Hilgard finding a 15-foot layer of jelly-like matter on the ocean side of a bar at the mouth of the Mississippi.[42] At the line of contact of the salt water of the ocean and the fresh water of the Tallebudgera and other rivers of southern Queensland, sunken ridges are developed whose persistence is explained by Barton[43] as due to precipitated colloidal matter serving as a binder for the coarser particles, thus leading to a certain degree of fixity of the deposits. The organic matter of natural waters has been stated to be incompatible with colloidal ferric oxide, one part of the latter precipitating ten parts of humus, the substances forming a flocculent precipitate whose settling entraps other matter in suspension.[44] On the other hand, the experiments of Gruner[45] have shown that larger quantities of iron are carried "as organic colloids or adsorbed by organic colloids" than as the carbonate, and Moore and Maynard[46] are of the opinion "that the iron going to make up large sedimentary iron formations was transported principally as a ferric oxide hydrosol, stabilized by organic matter."

Transportation by Streams of Matter Carried in Solution. Matter carried in solution by streams has more or less effect on the materials over which it moves. Various reactions may occur with these materials, leading to

[40] Johnston, J., and Williamson, E. D., Jour. Geol., vol. 24, 1916, footnote p. 734.

[41] Robinson, G. W., Pedology as a branch of geology, Geol. Mag., vol. 61, 1924, p. 449.

[42] Hilgard, E. W., Pop. Sci. Monthly, vol. 80, 1912, pp. 237–245.

[43] Barton, E. C., The work of colloids in sand bank and delta formation, Geog. Jour., vol. 51, 1918, pp. 100–115.

[44] Spring, W., Bull. Acad. Roy. des Sciences, etc., de Belgique, vol. 34, 1897, pp. 578–600.

[45] Gruner, J. W., The origin of sedimentary iron-formations: the Biwabik formation of the Mesabi Range, Econ. Geol., vol. 17, 1922, pp. 407–460.

[46] Moore, E. S., and Maynard, J. E., Solution, transportation and precipitation of iron and silica, Econ. Geol., vol. 24, 1929, pp. 298–302.

some deposition. Some dissolved matter may become trapped on the flood plains or in the pools during low water and thus be deposited. The substances in solution in a given stream may vary widely from place to place, thus proving deposition. The Arkansas River where it emerges from the Colorado Mountains at Canyon City has a salinity of 148 parts per million, with composition of the dissolved matter as shown in table 10; at Rockyford, nearly 100 miles lower down the stream, the salinity has increased to 2,134 parts per million, with composition as shown. The noteworthy changes are the great increase in sulphates and the decrease in silica and carbonates.[47]

The quantity carried in solution varies within extremely wide limits in different streams and in different parts of the same stream. Moreover, it

TABLE 10

	CANYON CITY	ROCKYFORD
CO_3	37.55	2.65
SO_4	14.62	60.69
Cl	3.77	4.89
Ca	20.24	12.78
Mg	5.13	3.76
Na	9.57	14.50
K	0.60	0.28
SiO_2	8.19	0.45
R_2O_3	0.33	0.00
	100.00	100.00

is not the same at all times.[48] It has been estimated that a cubic mile of average river water contains 420,000 tons of dissolved matter and that about 2,735,000,000 tons of dissolved substances are carried annually to the sea.[49] North America is thus losing around 474,000,000 tons per annum, and for the United States it is estimated that dissolved matter to the quantity of 270,000,000 tons is annually transported to the sea.[50]

The material transported varies with the river. Streams draining limestone regions are high in lime carbonate, and the quantity in some streams is so largely in excess of what may be carried in true solution that some of

[47] Headden, W. P., Bull. No. 82, Colorado Exper. Station, 1903.

[48] Wallace, R. C., Baker, W. F., and Ward, G., The Red River as an erosive agent, Trans. Roy. Soc. Canada, 1927, pp. 149–167.

[49] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 63; Murray, J., Scottish Geog. Mag., vol. 3, 1887, p. 65.

[50] Dole and Stabler, op. cit., p. 83.

it may be in the form of colloids or fine particles in suspension. Streams of central Kansas and Oklahoma, where many of the surface rocks are composed of gypsum and there are large salt deposits, may be high in these substances. Streams flowing from areas underlain by igneous rocks have small quantities of lime compared to those flowing from areas underlain by limestone, but may be high in silica. According to Johnston,[51] waters draining areas of crystalline rocks are characterized by high primary salinity[52] (large content of K and Na nitrates, sulphates, and chlorides) and high primary alkalinity (alkali carbonate content), whereas streams draining areas of sedimentary rocks have a high secondary alkalinity (content of sulphates and chlorides of lime and magnesia) and a high secondary salinity (carbonates and bicarbonates of lime and magnesia).

TABLE 11

	1	2
CO_2	33.40	35.15
SO_4	15.31	12.14
Cl	7.44	5.68
NO_3	1.15	0.90
Ca	19.36	20.39
Mg	4.87	3.41
Na	7.46	5.79
K	1.77	2.12
$(Fe, Al)2O_3$	0.64	2.75
SiO_2	8.60	11.67
	100.00	100.00

It is probable that everything is carried in solution, but only a few substances are present in large quantities. Those most important are shown in the above analyses, of which number 1 represents the average for all the streams of North America and number 2 the average for the world.[53] It seems certain that part, if not all, of the ferric and aluminum oxides and the silica are in the colloidal state and not in true solution.[54]

The ratio between dissolved and suspended matter ranges between wide limits. Streams having their drainage basins covered with dense vegeta-

[51] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv., Canada, 1921, pp. 25–26.

[52] Palmer, C., The geochemical interpretation of water analyses, Bull. 479, U. S. Geol. Surv., 1911.

[53] Clarke, F. W., op. cit., p. 119.

[54] See Wallace, Baker, and Ward, op. cit., pp. 164–166.

tion and those that pass through lakes have the ratio between dissolved and suspended matter much greater than unity; thus, the Kennebec at Waterville, Maine, has the ratio equal to 12,[55] whereas the average for the Hudson is 6.7. The ratio progressively decreases toward the south, being an average of 2.9 for the streams of the Middle Atlantic coast north of Virginia and an average of 0.82 for the southern Atlantic states. For the eastern coast of the Gulf of Mexico the average ratio is 0.93, and for the dryer states of the western Gulf region (disregarding one given by Dole and Stabler for Carlsbad, New Mexico) the ratio is 0.71. The average for the Mississippi below Minneapolis is 5.6; at Minneapolis it is 25. The average for the Missouri River is 0.40. For the waters of the St. Lawrence the suspended matter consists of merely a trace, whereas the dissolved matter ranges around a hundred parts per million. For the Colorado River the average ratio is 0.39. The average ratio for the United States is about 0.53.

It thus appears that streams draining the semi-arid parts of the country and those regions with considerable relief carry less dissolved than suspended matter, and this relation appears to find its greatest expression in the waters of the Rio Grande at El Paso, where the ratio is about 0.05 or 14,140 parts per million of suspended matter to 700 parts per million of dissolved matter. On the other hand, streams draining areas which are relatively low or covered with vegetation have the ratio of dissolved to suspended matter generally several times unity. In this computation the material transported by traction is not included.

These facts emphasize the close relation that exists between the conditions obtaining over the drainage areas of streams and the methods of transportation and kinds of material transported, and to some extent this should be expressed in the sediments ultimately deposited.

Transportation and Deposition in Standing Bodies of Water

Transportation and deposition in standing bodies of water are somewhat different from those of streams, both with respect to methods and effects. In streams, the material is continuously being shifted in the same general direction, and after the sediments have passed a place they are not wont to return thereto. Waves, on the other hand, may shift sediments over the same areas numerous times, the sediments thus traveling many miles and yet never reaching more than a few hundred yards from the places of starting.

The sediments in standing bodies of water are derived from contributions by streams, winds, and volcanoes; from the work of waves and currents through abrasion, impact, grinding, undermining, and solution; and from organisms. It is difficult to evaluate the quantity derived from each source,

[55] Dole and Stabler, op. cit., tables pp. 85–93.

but it may be suggested that the sediments derived from the shore by wave erosion probably constitute the largest quantity.

Transportation is accomplished by waves and currents.

The waves are constantly shifting and grinding all material exposed to their action, throwing the coarse and heavier particles farther up the beach, while the lighter particles are carried out to sea. The quick shorewards rush of a wave carries all before it, its churning action lifting all types of material off the bottom, but during the period of momentary rest prior to the return movement of the wave waters, the larger and heavier particles fall. The return movement of water is of greater duration and therefore of lesser velocity; it takes place below the succeeding waves and steadily rakes the lighter particles along the floor of the ocean into deeper parts, but lacks the energy necessary for carrying the heavier particles.[56]

The method of wave transportation is stated by Johnson as follows:

On a flat bottom oscillating waves will move débris prevailingly shorewards, but if the slope be steep enough, the same waves may cause material to migrate seawards, or coarse débris may be propelled shoreward and fine débris seaward. If the waves belong to the class of true waves of translation, the débris may be transported landward even on a sloping bottom. Waves breaking on the beach drive material up the slope until continued accumulation makes the slope so steep that the backwash returns all to the breaker zone. If the beach slope is too steep for a given set of waves, the backwash will return more material than was brought by the forward rushing current and the beach will suffer erosion. If the undertow is too strong it may prevail over the landward component of wave motion and cause the bottom débris to move continuously seaward; but if the waters piling up along a coast escape laterally as long-shore currents, the débris may first move landward and then suffer longshore transportation under the influence of these currents.[57]

On sand and gravel beaches each onrush of a wave carries more water than the flowback, as some water sinks into the materials of the beaches, thus proportionately decreasing transportation outward from the beaches. The water thus sinking into the beach materials flows out between the onrush and the flowback, but this water has low competency and capacity. The onrush commonly is stronger than the flowback, as gravity alone draws the water down the slope. The net result is that the coarser materials tend to stay with the beaches and the finer to be moved to deeper waters.[58] This wash of the waves over a beach produces much abrasion and grinding. At the Dumbarton Bridge over San Francisco Bay at Palo Alto a count of the inwash of the small waves gave twenty-two per minute. This moved many particles backward and forward twenty-two times per minute.

[56] Barton, E. C., The work of colloids in sandbank and delta formation, Geog. Jour. vol. 51, 1918, p. 106.

[57] Johnson, D. W., Shore processes and shoreline development, 1919, pp. 105–106.

[58] Landon, R. E., An analysis of beach pebble abrasion and transportation, Jour. Geol., vol. 38, 1930, pp. 437–476. Landon states that spherical pebbles tend to seek deep water and flat pebbles to stay with the beach.

The general difference in the directions of transportation of the coarse and large particles as distinguished from the fine does not appear to have received the appreciation it deserves,[59] and it certainly has great importance in connection with unconformities. Observations made on Anticosti and the Mingan Islands, where occur some of the most extensive wave-cut terraces which are known, have shown that as a sea with stationary sea level progresses inland, the coarser sediments generally stay with the beach, whereas the finer sediments commonly are carried to deeper water. The invading sea thus leaves behind it a wave-cut rock surface uncovered by sediments, and this surface cannot receive deposits of a permanent character until rise of sea level submerges it below the depth of wave cutting, following which it will receive sediments deposited off-shore. Shore currents transport materials of various degrees of fineness and coarseness along shore, but the competency of current transportation is low, and large particles are not likely to travel far from their places of origin. Where bends of the coast direct currents across bays or seaward, some of the coarser particles move to deep water. Where the shore or littoral currents set in from both sides toward the head of a bay, the undertow at the head of this bay is commonly stronger than either of the shore currents, and this undertow may transport coarse material into the deeper portions of a bay or even out to sea.[60] Thus, it has been shown that in parts of San Francisco Bay muds locally are deposited inshore in shallow water; sands occur farther out in deeper waters; and the gravels are in the deepest waters.[61]

Rate of Settling of Particles. The rate of settling of particles varies with the dimensions, the shapes, and the specific gravity, the larger, the more spherical, and those of higher specific gravity falling the faster. For the rate of falling of spherical particles Stokes[62] deduced the following formula:

$$V = \frac{2}{9} gr^2 \frac{(s - s')}{c},$$

V being the rate of falling, r the radius of the particles, s the specific gravity of the particles, s' the specific gravity of the liquid, c the viscosity coef-

[59] Gregory, H. E., The formation and distribution of fluviatile and marine gravels, Am. Jour. Sci., vol. 39, 1915, p. 501.

[60] The existence of an undertow has been denied, but the writer's experience in the bays of Anticosti Island has convinced him that strong currents set seaward from the heads of bays under certain conditions.

[61] Louderback, G. D., Preliminary results of a study of the San Francisco Bay sediments, Bull. Geol. Soc. Am., vol. 31, 1920, pp. 123–124; Sumner, F. B., Louderback, G. D., Schmitt, W. L., and Johnston, E. C., A report upon the physical conditions in San Francisco Bay, etc., Univ. California Publ. in Zool., vol. 14, no. 1, 1914, p. 5.

[62] Stokes, G. G., Cambridge Philos. Trans., vol. 8, 1845, p. 287; vol. 9, 1851, p. 8; Mathematical and Physical Papers, vol. 1, 1901, p. 75.

ficient of the liquid, and g the gravity acceleration; c is not constant for a given medium, but decreases with rise of temperature as shown below for water.[63]

Temperature	*Centipoises*
0°C	1.7921
4°C	1.5674
10°C	1.3097
20°C	1.0050
30°C	0.8007
40°C	0.6560
50°C	0.5494
60°C	0.4688

It does not seem probable that the viscosity and density of water are important for particles of sand or larger dimensions, but they undoubtedly have great influence in holding the smaller particles in suspension, and it has been shown that the settling of fine particles in distilled waters is very much more rapid in high than in low temperatures.[64] Allen's investigation of the Stokes formula showed that for particles above certain dimensions the actual velocities are greater than may be deduced therefrom.[65]

The Stokes formula is based on five assumptions, as follows:

1. The discontinuites of the fluid are small compared with the sizes of the particles.
2. In comparison with the falling particles the fluid is of infinite expanse.
3. The particles are spheres, smooth and rigid.
4. There is no slip at the surface between particles and fluid.
5. The velocity of the particles is small.[66]

Millikan's investigation of the formula with respect to the falling of oil droplets in air showed that a correction is required in that case.[67] Such a correction may not, however, be necessary for the falling of solids in liquids.

The Stokes formula applies to particles of spherical shape, which is not the ordinary shape of sedimentary particles. Odén[68] formulated a generalization which is stated to hold for particles of other shapes. The generalization employs the conception of the effective radius, or the radius of a perfect

[63] Fowle, F. E., Smithsonian physical tables, Smithsonian Misc. Collections, vol. 71, No. 1. 3rd reprint, 1927, p. 155. See also Intern. Critical Tables, vol. 5, 1929, p. 10.

[64] Barus, C., Subsidence of fine solid particles in liquids, Bull. 36, U. S. Geol. Surv., 1886, pp. 20–24.

[65] Allen, H. S., The motion of a sphere in a viscous fluid, Philos. Mag., vol. 50, 1900, pp. 323–338.

[66] Arnold, H. D., Limitations imposed by slip and inertia terms upon Stokes' law for the motion of spheres through liquids, Philos. Mag., vol. 22, 1911, pp. 755–775.

[67] Millikan, R. A., Stokes' law of fall completely corrected, Proc. Nat. Acad. Sci., vol. 3, 1923, pp. 67–70.

[68] Odén, S., On the size of particles in deep-sea deposits, Proc. Roy. Soc. Edinburgh, vol. 36, 1915–1916, pp. 219–236.

sphere of the same material which would sink in a given fluid at the same rate as the given particle. This formula was not designed to determine the rate of fall, but from the rate of fall to determine the effective radius. The Odén formula has been discussed by Knott[69] and Vaughan,[70] and for detail the original articles should be consulted.

Allen found the Stokes formula to hold for particles of less than 85 microns.[71] Odén states that a particle of 0.3 microns diameter requires 100 hours to settle through 10 cm. of fresh water, and 14 months to settle 10 meters.[72]

Hazen's[73] studies on the rate of settling gave the data shown in table 12.

TABLE 12

DIAMETERS OF PARTICLES IN MILLIMETERS	RATE OF SETTLING IN MILLIMETERS PER SECOND TEMPERATURE, 15°C.	
1.00	100	Based on experiment
0.80	83	
0.60	63	
0.40	42	
0.20	21	
0.10	8	
0.08	6.0	Interpolated from curve
0.06	3.8	
0.04	2.1	
0.02	0.62	Derived from formula
0.01	0.154	
0.008	0.098	
0.006	0.055	
0.004	0.0247	
0.002	0.0062	
0.001	0.00154	
0.0001	0.0000154	

It is assumed that the specific gravity of the particles approximated that of quartz, which with diameters of 1 micron or 0.001 mm. would settle about a meter in one month, a rate which would be entirely neutralized by currents. From this it follows that particles of small dimension may attain ocean-wide distributions.

[69] Knott, C. G., Mathematical note on the fall of small particles through liquid columns, Proc. Roy. Soc. Edinburgh, vol. 36, 1915–1916, pp. 237–239.

[70] Vaughan, T. W., Rept. Comm. Sed., Nat. Research Council, 1923, pp. 41–49.

[71] Allen, H. S., op. cit.

[72] Odén, S., Allgemeine Einleitung zur Chemie und physikalischen Chemie der Tone, Bull. Geol. Inst. Upsala, vol. 15, 1916, pp. 174–194 (191).

[73] Hazen, A., On sedimentation, Trans. Am. Soc. Civil Engineers, vol. 53, 1914, pp. 45–88 (63).

VARIATIONS IN DEPOSITION. Sediments adjacent to shores tend to vary greatly in thickness and character from place to place and from time to time, each deposit grading laterally and vertically into others of different thicknesses and characters. Deep-water sediments far from land have relatively uniform distribution over wide areas, which in turn implies considerable uniformity in vertical sequence. Bottoms at the depth of a base level of deposition receive no permanent deposits.

EFFECTS ON MATERIALS TRANSPORTED. The constantly repeated washing of sands and coarser particles in the shallow waters adjacent to shores leads to a high degree of rounding for particles above the diameter of 0.1 mm. Substitution of values in the formula given on page 76 indicates that rounding in water cannot be carried to the limit noted under wind action. Chattermarks may be made on all the larger particles; they are not as a rule made on particles smaller than the pebble grade because of the inability of water to bring together particles of smaller dimensions with the force necessary for their production. As there is always considerable solution, the small particles may have shiny surfaces,[74] but particles of other production may be included and retain the characters which they had previously received. Bed-rock bottoms over which the particles move become polished. This is particularly obvious in the tidal belt and the adjacent shallow water.

The pebbles and larger particles which are transported to the beaches may have any shape. The oft-made statement that the pebbles, etc., of lake and sea shores are characteristically of disk-shape does not appear to be in harmony with observation, and it is not correct to assume that particles of this shape occur only in these environments, as they may be found among material of other origin. They are very abundant, for example, among the Pleistocene fluvial gravels about the Big Horn, Bear Tooth, and probably other western mountains, and they may be collected in any fluvioglacial deposit. The occurrence of pebbles of this shape seems to be very largely dependent upon the initial shapes of the particles.[75] Their abundance on some beaches is apparently due to a source in the vicinity which yields an abundance of fragments with one small and two larger dimensions, or has been brought about through segregation of pebbles of this shape by wave action, such having been separated from those more spherical because of shape and greater surface in proportion to volume. If the particles of a beach are of adequate dimension and shape, they may shingle over each other in such a way as to slope toward the water and be successively overlapped by those above. Exceptions, however, are numerous.

[74] Galloway, J. J., Value of the physical characters of sand grains in the interpretation of the origin of sandstone, Abstract, Bull. Geol. Soc. Am., vol. 33, 1922, p. 104.

[75] Wentworth, C. K., The shapes of pebbles, Prof. Paper 131-C, U. S. Geol. Surv., 1922.

Competency, Capacity and Load. The competency and capacity of salt water, because of its greater density, are higher than is the case for fresh waters when other conditions are equal.

Currents in lakes and seas usually have low competency and capacity because of low velocity. The load, generally only a fraction of the capacity, consists ordinarily of sand, silt, and clay particles and living and dead organic matter. On the Holland coast in a calm sea Vervey found that a cubic meter of surface water at high tide contained 109 grams of sand and 1303 grams of clay and silt (schlamm). At ebb tide, also in a calm sea, the same quantity of surface water contained 304 grams of sand and 1094 grams of silt and clay. At the distance of one meter above the bottom at high tide the quantity was 1094 grams of sand and 1861 grams of clay and silt; at ebb tide and the same distance above the bottom the quantities were 1062 grams of sand and 2980 grams of clay and silt.[76] These loads, as Penck observed, are as great as those of mountain streams in high water. Hagen[77] has shown that the clay content of sea water near the bottom is from one-fifth to one-third greater than at the surface and generally is greater at rising than at ebb tide.

It is thought that considerable quantities of silt and clay are carried long distances seaward from the shores and that the total quantity of fine terrigenous materials in the waters over the deep ocean basins is probably extremely large. Murray and Renard[78] found that a sample from the middle of the north Atlantic indicated a content per cubic mile of 1601 tons, one from the Mediterranean 2031 tons, a sample from the North Sea gave 1946 tons, and one from the Indian Ocean 264 tons. Sea water with a salinity of 1.025 after remaining thirty days at rest still had 625 tons of finely divided matter in suspension in each cubic mile.[79] Reade and Holland[80] seem to be of the opinion that the above figures may be too small, and they state that "the sea may hold, carry about and distribute such fine or microscopic sediments in quantities, if not commensurate with, second only to the matter held in solution." Most of this inorganic matter is probably of colloidal dimensions, but some of it may be of the magnitude of

[76] Cited by Penck, A., Morphologie der Erdoberfläche, vol. 2, 1894, p. 480, from Vervey, W., Waterstaatkundige beschrijving van Nederland, 1890, p. 83.

[77] Cited by Penck, A., op. cit., p. 496, from Hagen, G., Über die Flut- und Bodenverhältnisse des Preussischen Jadegebietes, Monatsber. d. k. preuss. Akad. d. Wiss., Berlin, 1856, pp. 339–353.

[78] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, p. 287.

[79] Murray, J., and Irvine, R., On silica and siliceous remains of organisms in modern seas, Proc. Roy. Soc. Edinburgh, vol. 18, 1891, pp. 241–244; Murray and Renard, op. cit., p. 340.

[80] Reade, T. M., and Holland, P., Sands and sediments, pt. iii, Proc. Liverpool Geol. Soc., vol. 10, 1905, p. 156.

silt and sand grains enmeshed in jelly-like organic materials the low density of which enables it to float long distances in waters of negligible competency. Such jelly-like materials have been described by Petersen[81] from Danish waters and by Raymond and Stetson from Massachusetts Bay[82] Samples from the latter waters contained much fine sand and silt and three gallons of surface waters containing this "jelly" yielded 0.2604 gram of fine sand and silt. Evidently this "jelly" may be a factor of importance in increasing the competency of salt waters. The well rounded grains of quartz found by Reade and Holland in sediments from the deep bottoms of the Atlantic may have been transported in such "jelly." The total quantity of sedimentary materials in suspension in ocean waters must attain billions of tons.

The velocities attained by waves of translation are often very great, giving large capacity and competency. Except locally, the load is far below the capacity.

DISTRIBUTION OF SEDIMENTS IN STANDING BODIES OF WATER. In standing bodies of water the coarser materials generally tend to remain with the beach, whereas the finer are shifted about over the bottom until they attain depths where waves and current no longer affect them. It does not follow, however, that all coarse materials remain adjacent to the beach, or that beaches and the adjacent shallow waters are devoid of fine materials. Sediments many miles from shores may be coarser than those adjacent to shores. Beaches protected from strong waves may become mud flats or even swamps, and certain combinations of conditions may carry extremely coarse sediments to deep waters and some distance from shores. The fine sediments are transported seaward in suspension, these consisting of sands, silts, and clays. Synchronously, traction moves sands, gravels, pebbles, and larger particles in the same direction. A storm may transport sediments seaward in such large quantities as to bury multitudes of organisms, thus preserving their hard parts from destruction by scavenger animals and solution. Some vagrant benthonic animals might relieve themselves from the smothering sediments, but sessile benthos, such as brachiopods, could not do so, and they would remain in the sediments just as they died. The wonderful preservation of brachiopods, trilobites, and other fossils in the shale beds of Cincinnati, Anticosti, Gotland, and elsewhere is considered to represent such rapid deposition, whereas the adjacent beds with few fossils may represent much slower accumulation and concomitantly more complete scavenger action, the former not necessarily indicating a greater abundance

[81] Petersen, C. G. J., Rept. Danish Biol. Sta., vol. 20, 1911.

[82] Raymond, P. E., and Stetson, H. C., A new factor in the transportation and distribution of marine sediments, Science, vol. 73, 1931, pp. 105–106.

of life, but a more rapid deposition of sediments. This view has been previously stated by Barrell[83] Wepfer, and others and it is probable that absence of fossils in many cases is a consequence of slow deposition.

It has been shown by Trask that the mechanical composition of marine sediments varies with the configuration of the bottom, the finer sediments tending to accumulate in basins, the coarser on the high parts of the bottom and on divides between basins; and that submarine topography influences the mechanical nature of the sediments to a greater degree than does depth of the bottom or distance from the shore. Sediments collected in Behring Sea and Davis Strait on bottoms many miles from the coast in depths of 500 or more fathoms are sands, whereas sediments from the continental platforms nearer shore and in much shallower waters are silts and clays. This distribution seems to be due to the tides and currents which are more effective on high places than on low and over some bottoms of the deeper waters than on some in much shallower waters, with the result that the finer sediments ultimately drift into the places of lesser agitation and the coarser materials remain on those bottoms of greater water movement.[84]

In bodies of fresh water, extremely fine sediments do not aggregate so readily as in salt water, and thus may settle slowly and widely over entire bottoms.

The bottoms of seas and large lakes become adjusted by deposition or erosion to the conditions prevailing at each place, and when so adjusted, remain constant in position with respect to the water surface. The bottom is then at the profile of equilibrium for the existing conditions, or, in other words, is a temporary base level of deposition, and permanent deposition on such bottoms has ceased. As pointed out by Eaton,[85] there are fluctuations in the position of the profile of equilibrium consequent to a given combination of conditions, these fluctuations arising from weather conditions, variations in nature of sediments transported, etc. Bottoms which are above the profile of equilibrium for a given set of conditions are eroded until the profile is attained; bottoms below the profile receive deposits to that level. Bottoms coinciding with the profile of equilibrium receive no permanent deposits, the sediments being shifted seaward until bottoms below the pro-

[83] Barrell, J., Rhythms and the measurement of geologic time, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 798, 807; Wepfer, E., Ein wichtiger Grund für die Lückenhaftigkeit paläontologischen Ueberlieferung, Centralbl. f. Min., etc., 1916, pp. 105–113 (107); Terrestrische Einflüsse bie der marinen Sedimentation und ihre Bedeutung, Zeits. d. d. geol. Gesell., vol. 74, 1922, pp. 39–47 (43).

[84] Trask, P. D., Sedimentation in the Channel Islands region, California, Econ. Geol., vol. 26, 1931, pp. 24–43. See also by Trask, Rept. Comm. Sed., Nat. Research Council, 1932

[85] Eaton, J. E., The bi-passing discontinuous deposition of sedimentary materials, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 713–761.

file of equilibrium are reached. Wave and current action may slowly carry bottoms at the profile of equilibrium to wave base, and this may be considered the final base level of deposition or the ultimate profile of equilibrium. For practical purposes the deepest position of wave base on an open shore may be considered to approximate 600 feet.[86] In the youthful and mature stages of the marine erosion cycle, when the shore is open to direct attack, much sediment is deposited over a shallow bottom. In the old-age stage of the cycle, when neither the lands nor the shores are supplying much in the way of mechanical sediments and the shores have been cut far back, these earlier deposits will be cut away to the base level of erosion[87] (fig. 3). Streams in the earlier stages of the stream cycle of erosion may bring vast volumes of sediments to the places where they reach the sea and build up the bottoms

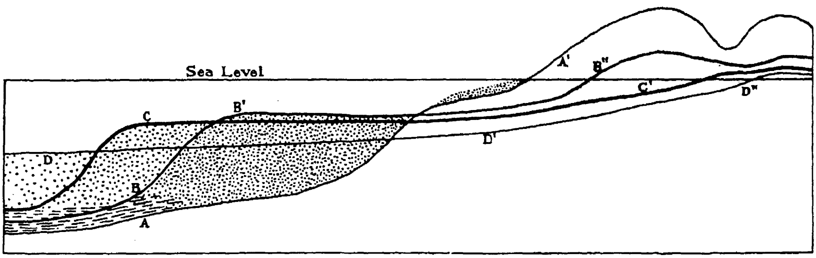

FIG. 3. DEVELOPMENT OF THE MARINE CYCLE FROM MATURITY TO OLD AGE ON A SHORELINE OF SUBMERGENCE

AA′, mature profile on sea bottom and on land; BB′B″, profile in early old age; CC′, profile in advanced old age; DD′D″, profile when the bottom has been brought to the base level of deposition or erosion (wave base). The shore deposits are not shown. Modified after Johnson, D. W., Shore processes and shoreline development, p. 224.

to sea level or even above sea level, but on the completion of the delta cycle, all of the material above the base level of deposition will have been removed.

The slope of the base level of deposition varies with the bodies of water, being steepest in those with strong wave and current action and gentlest in small ponds. It is steepest nearest the shore and becomes tangent to the horizontal toward the sea.

According to Barrell, the variations in depth of the profile of equilibrium in a wide shelf sea in mid-temperate latitude are as shown in table 13.

For seas of different character Barrell suggested that depths as shown in table 14 would approximate the position of the profile.

The profiles of equilibrium and base levels of deposition are somewhat

[86] Barrell, J., op. cit., pp. 777–779.
[87] Johnson, D. W., Shore processes and shoreline development, 1919, p. 226.

different in lakes than in the open sea, in that the former may be filled and hence permanent deposits may be made above the level of the water. To some extent this is also true for those epeiric seas from which the sediments cannot be easily shifted to the deeper waters of the open ocean.

TABLE 13

	DISTANCE FROM THE SHORE IN MILES						
	1	2	3	5	10	20	100
Depth in feet.......	7.5	11	13.5	15.5	18	23	50

TABLE 14

DEPTH IN FEET OF VARIOUS TYPES OF WATER BODIES

TYPE OF WATER BODIES	DISTANCE FROM THE SHORE IN MILES				
	5	10	20	80	100
	feet	*feet*	*feet*	*feet*	*feet*
Stormy shelf seas....................	95	110	140	300	300
Stormy epeiric seas..................	55	70	90	110	110
Quiet epeiric seas....................	35	50	70	90	90
Wide lagoons..........................	15	15			
Playas...............................	0–5				0–10

From what has been stated it follows that all bottoms below the depth of wave action may receive permanent deposits, that bottoms beneath the profile of equilibrium and above the depth of wave action may receive deposits which persist for longer or shorter periods of time, and that bottoms which are at or above the profile of equilibrium can receive no permanent deposits. All deposits above the depth of wave action will be removed if the marine cycle is carried to completion.

Bodies of water with steep bottom profiles are likely to have coarser materials shifted seaward than those with more gentle profiles. If the shores are cliffed, and relatively deep water exists at the bases of the cliffs, it is thought that under certain conditions particles of pebble, cobble, and even boulder dimensions may be carried outward over bottoms with gentle profiles, and deposited at considerable distances from the shores.

RATES OF DEPOSITION AND THICKNESS OF DEPOSITS. The thicknesses of deposits in open marine waters are intimately related to supply of material, the rapidity of rise of sea level (or sinking of the bottom), and the depth of the base level of deposition, and, in general, deposits cannot be built to a greater permanent thickness than the distance between the bottom

and the position of this level. Subsiding bottoms permit a thickness to accumulate equal to the amount of subsidence plus the thickness given above.

The determination of the rates of deposition of sediments has been theoretically arrived at in two ways: namely, by comparing the rate of erosion of a given region with the area of the basin receiving the sediments therefrom, and by dividing the thickness deposited during a given geologic period by the duration of that period as determined by other methods. Neither of these methods can be said to approach accuracy with the slightest degree of precision. The former has been used by Walcott for ancient deposits, but the difficulty lay in obtaining data both as to the area which underwent erosion and the area of the basin of deposition, and there was the additional difficulty that the rate of erosion was not known. Walcott[88] obtained a rate of deposition of one foot in fifty years, which according to Barrell is at least fifteen times too large.[89] All that may be said for this method is that it is a guess in scientific garb.

The determination of the rate of deposition obtained by dividing the thickness deposited during a given geologic period by the duration of the period wholly disregards the times of no deposition as represented by unconformities, diastems, and still lesser interruptions, and the matter is further complicated by the fact that as yet no way has been learned by which the duration of a geologic period may be even approximately determined. The Upper Triassic of the Island of Timor is but 7 feet thick, but it represents all of Karnian and Norian time—millions of years—during the whole of which the bottom must have been very close to the level of wave base.[90] The Tertiary of the Ventura Quadrangle of California has a thickness exceeding 30,000 feet,[91] and yet it may not represent so long a time as the 7 feet given above.

Determinations of the rates of deposition by direct observation have been made in a few instances, but the observations apply only to limited areas. Direct observations extending over a large basin have yet to be made, and are extremely desirable.

Some of the best data which have been obtained apply to the upward building of coral reefs. Dana[92] estimated that this is above $\frac{1}{16}$ inch each

[88] Walcott, C. D., Ann. Rept. Smithsonian Inst. for 1893, 1894, pp. 310–314; Jour. Geol., vol. 1, 1893, pp. 639–676.

[89] Barrell, J., op. cit., p. 817.

[90] Arthaber, G. von, Jaarb. Mijnwesen in Ned.-Indie, Verh. II, 1926. Review by Schuchert, C., Am. Jour. Sci., vol. 16, 1928, p. 459.

[91] Cartwright, L. D., Jr., Sedimentation of the Pico formation in the Ventura Quadrangle, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 235–270.

[92] Dana, J. D., Corals and coral islands, 1890, p. 254.

year, giving 190 years for a foot, or 5 feet in 1000 years. Le Conte[93] found in the Tortugas that there was an annual variation of the water level of around 3 inches and that the coral growths kept pace with the rise of water, only to die and be torn down when the water fell. This does not mean, however, a rise of the reef of 3 inches each year, but only of the individual corals. Vaughan came to the conclusion that *Orbicella annularis*, the principal reef-builder of the Pleistocene and Recent West Indian reefs, grows at the rate of 5 to 7 mm. per year.[94] At the rate of 6 mm. per year, a reef 150 feet thick could form in 7620 years, and at the maximum rate of 7 mm. per year, 6531 years would be required to form a reef of the same thickness. *Acropora palmata*, a species of more rapid growth, could form a reef of equal thickness in 1800 years. In the Pacific, according to Gardiner, growth seems to be more rapid, and a reef of that thickness could be formed in 1000 years.[95] Pollock[96] estimated the rate of growth of the fringing reef of Oahu as approximately one foot in 300 years.

Mechanical sediments accumulate most rapidly adjacent to coasts where deep waters are close to the shore, as such bottoms receive over limited areas the sediments which on bottoms with gentler profiles are spread over wider areas. Bottoms about the mouths of rivers have high rates of deposition. Thus, the places where the Mississippi is advancing its delta into the Gulf may rise many feet in the course of a year. On July 25, 1904, a firm shell bottom was made in a salt-water lake of the delta; on July 29 this bottom was buried beneath 12 inches of mud, a rate of deposition of 1 foot in four days.[97] At the mouth of Fraser River deposition is taking place at the average rate of 20 feet per annum.[98]

The rate of deposition appears to be very large where shore currents cross bays, as thick sand bars are known to be formed in very short periods of time. Just seaward of where a base level of deposition (temporary or permanent) leaves bottom, deposition at times must be very rapid, particularly during storms, when the deposits of a single day may be many times greater and thicker than the deposits of several previous years.

Deposition over the deep sea probably is very slow, but it may be more

[93] Le Conte, J., Am. Jour. Sci., vol. 10, 1875, pp. 34–36.

[94] Vaughan, T. W., Corals and the formation of coral reefs, Ann. Rept. Smithsonian Inst. for 1917, 1919, pp. 210–214; see also Mayor, A. G., Growth-rate of Samoan corals, Pub. 340, Carnegie Inst. of Washington, 1924, pp. 52, et al.

[95] Gardiner, J. S., Fauna and geography of the Maldive and Laccadive archipelagoes, vol. 1, 1903, pp. 327–333.

[96] Pollock, J. B., Fringing and fossil coral reefs of Oahu, Bull. 55, Bishop Mus., 1928.

[97] Kellogg, J. L., Notes on marine mollusks of Louisiana, Bull. 3, Gulf Biol. Station, 1905, p. 28.

[98] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv. Canada, 1921, p. 37.

rapid than first impressions suggest. According to Murray,[99] "In the North Atlantic, telegraph operators think there are reasons for supposing that about 1 inch of Globigerina ooze accumulated in ten years," and it has been suggested that the rate of deposition of inorganic constituents over the deep ocean basin approximates one foot in 87,100 years.[100]

The relative rates of deposition of the various types of sediments are unknown. Ulrich[101] assumed that the time involved[102] in depositing 7 feet of shales and sandstones is about equal to that necessary for the deposition of a foot of limestone, but he frankly admits that the assumed ratio is a purely arbitrary one. Smith[103] assumed a ratio of sandstone to limestone deposition of 10 to 1. It "is usually considered that a sandstone series represents a shorter period than the same thickness of shale or limestone, but the intervals when nothing was laid down, and still more the frequency with which erosion followed fast on deposition, may more than redress the balance."[104] A cross-laminated sandstone unit usually is assumed to represent a short interval of time, but it is equally probable that each bed may have been deposited scores of times before the final deposition and that a thin bed of a couple of inches may represent the accumulations of thousands of years.

Causes of Deposition from Water

The causes of deposition from water vary with the methods of transportation and the nature of the materials transported. Matter carried in solution is deposited as a result of evaporation, chemical reactions, and physico-chemical and organic processes. None of these is considered in this connection.

Sediments carried by traction are deposited when the movement of the water is lowered to the extent that its competency falls below that necessary for transportation of the particles considered, and in still water all transportation by traction ceases. The lowering of competency also leads to the de-

[99] Murray, J., Science of the sea, edited by G. H. Fowler, London, 1912, p. 209.

[100] Twenhofel, W. H., Magnitude of the sediments beneath the deep sea, Bull. Geol. Soc. Am., vol. 40, 1929, p. 391.

[101] Ulrich, E. O., Revision of the Paleozoic systems, Bull. Geol. Soc. Am., vol. 22, p. 381.

[102] It probably should never be assumed that the rate of deposition of a given sediment has been uniform or continuous. There may have been many interruptions of all magnitudes from those represented by unconformities to the minor interruptions arising from changes in local currents. Likewise, the range in the rate of deposition probably is extremely great.

[103] Smith, J. P., The geologic record of California, Jour. Geol., vol. 18, 1910, pp. 216–227. For a complete consideration of ratios of deposition see Schuchert, C., in Physics of the Earth, Bull. 80, Nat. Research Council, 1931, pp. 33–53.

[104] Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 24, 1913, p. 244.

position of the larger suspended particles, the rate of settling depending on the sizes and specific gravities of the particles, the density and temperature of the medium, and the extent of lowering of velocity. As all surface waters are subject to more or less agitation most of the time, some competency is almost always present. Small non-colloid particles thus tend to remain in suspension so long as they do not become aggregated. Particles of colloidal dimension in suspension in absolutely quiet distilled water under certain conditions will float indefinitely, and with very slight agitation small visible particles under like conditions would take an extremely long time before coming to deposition. In ordinary natural waters, however, the conditions of indefinite suspension seem rarely to be realized because of flocculation or coagulation,[105] whereby the particles merge with each other and thus increase their volume sufficiently to cause settling.[106] "All colloidal particles bear a charge of electricity which may be either positive or negative according to the nature of the colloid."[107] "When two colloidal sols of opposite electric charge are mixed, they mutually precipitate each other, the particles being attracted to one another and, in coalescing, form larger masses which settle rapidly."[108] It has been found that (1) small additions of a colloid of different sign produce no precipitation, (2) further additions cause flocculative activity to appear, (3) ultimately a proportion is reached causing immediate precipitation, and (4) great excess of added colloid may prevent precipitation.[108]

Colloids are also precipitated by electrolytes in solution. As long as the electrolytes and colloids in a given water have like electric signs, the colloids remain in suspension. If electrolytes of opposite sign are introduced, coagulation and settling are initiated. The flocculating ability seems to bear some relation to valency, divalent ions having greater effect than monovalent, and trivalent greater than either.[109] However, there does not seem to be general agreement on this point. According to Murray,[110] the precipitation of colloids by electrolytes depends on (1) the effects of ions of opposite electric charge, (2) the effects of valency, (3) the modifying action

[105] "Coagulation is the change of a suitable colloid to a jellylike state," Wells, R. C. Rept. Comm. Sed., Nat. Research Council, 1923, p. 50. Flocculation is the union of suspended particles to form larger aggregates. The two terms are used more or less interchangeably.

[106] Boswell, P. G. H., The action of colloids in precipitating fine-grained sediments, Geol. Mag., vol. 67, 1930, pp. 372–381. This paper contains an excellent experimental study of the action of colloids.

[107] Searle, A. B., The chemistry and physics of clays and other ceramic materials, 1924, p. 228.

[108] Searle, A. B., op. cit., pp. 230–231; Wells, R. C., op. cit., pp. 50–52.

[109] Holmes, H. W., Laboratory manual of colloid chemistry, 1922, p. 22.

[110] Murray, H. D., Chem. News, vol. 123, 1921, pp. 277–279.

of ions of the same sign, (4) possible adsorption of equivalent quantities of ions, (5) minimum necessary concentration of electrolytes, and (6) possible effect of an ion originally present.

The charge carried by colloids appears to depend largely on the environment of the suspended particles, but, in general, oxides, hydroxides, and colloids of readily oxidizable minerals bear a positive charge, whereas materials not readily oxidized bear negative charges.[111] This must not, however, be taken too literally, since "silica, clay, and humus bear negative charges, whilst alumina, ferric oxide and hydroxide, lime, magnesia, and the hydroxides of chromium, copper, aluminum, zirconium, titanium, etc., are positively charged."[111] Basic dyes are also positive; acid dyes are negative. Flocculation is accelerated by acids and calcium oxide and hydroxide, but not by other alkalies, the calcium oxide and hydroxide thus being exceptional.[112] The salt content necessary for flocculation varies inversely as the size of the particles.[113] Silt and most insoluble substances are most easily flocculated by calcium salts in neutral solutions,[113] but clay of soils is more readily flocculated from alkaline solutions.[113] Calcium nitrate is a better flocculent of silt than calcium hydroxide, whereas clay in alkaline solutions is more readily flocculated by calcium hydroxide than by calcium nitrate. Excess of electrolytes usually gives large flocculation.

The flocculent power of some electrolytes is given by Searle as follows:[114]

Hydrochloric acid	30	Potassium nitrate	2
Calcium chloride	15	Sodium nitrate	1
Potassium chloride	3	Sulphuric acid	20
Sodium chloride	1	Calcium sulphate	5
Nitric acid	28	Potassium sulphate	1
Calcium nitrate	10	Sodium sulphate	0.5

Deflocculation, also known as peptization, may be brought about by the addition of suitable electrolytes and shaking.[115] It is Trowbridge's opinion that deflocculation will not be particularly effective with colloids associated with coarser grades due to the colloids adhering to the sands, silts, and clays and settling with them.[116] Materials placed in suspension after once having been flocculated and precipitated are more quickly deposited

[111] Searle, A. B., op. cit., pp. 228–229.

[112] Lyon, Fippin, and Buckman, Soils, their properties and management, 1919, p. 159.

[113] Comber, N. M., Jour. Agriculture Sci., vol. 10, 1920, pp. 425–436 (436); Odén, S., Bull. Geol. Inst. Upsala, vol. 15, 1916, p. 192.

[114] Searle, A. B., op. cit., p. 245.

[115] Odén, S., op. cit., p. 192; Wells, R. C., op. cit., pp. 50–52; Searle, op. cit., pp. 246–249.

[116] Trowbridge, A. C., Rept. Comm. Sed., Nat. Research Council, 1923, pp. 57–59; Littlefield, M., Ibid., 1923, pp. 59–61.

the second and succeeding times than they were the first time, provided the waters are not changed.

Many colloidal sols are made stable by absorbing a minute quantity of salts or acids. Thus, stable silicic acid sol always contains traces of potassium, sodium and chlorine; whilst stable ferric hydroxide sol contains a trace of ferric chloride. If the traces are removed by dialysis the sols become unstable.

When a stable colloid, such as gelatin, and a less stable colloid of the same electric sign are acted upon by an electrolyte of opposite sign which is sufficiently concentrated to coagulate the less stable colloid, but not the more stable one, the latter may act as a protective agent and prevent the coagulation and precipitation of the less stable colloid. [Colloids thus preventing flocculation are designated protective.] The black colloidal matter of soils (humus), gelatin, peptone, and many organic colloids are very effective protective agents and prevent precipitation or flocculation.[117]

A striking property of some, perhaps all, colloids is the ability to take soluble salts from solution, the process being one of selective adsorption.

Sorting by Water[118]

Sorting of sediments by water is a consequence of the three different ways by which they are transported, and also is due to the different competencies arising from different velocities. Sorting of particles above colloidal dimensions is done according to specific gravity, size, and shape. Large and spherical particles and those of high specific gravity come to rest before others. This associates small particles of heavy substances, as gold, tin, etc., with larger particles of quartz or other substances of lower specific gravity. As already noted, the abundance of disk-shaped pebbles on some beaches may be due to sorting. The locally abundant presence of mica flakes, particles of garnet and magnetite, and fragments of shells is due to sorting. The variations in velocity and methods of transportation lead to the deposition of different grades of material over a given area at different times.

Sorting of mechanical sediments is favored by prolonged transportation, vigorous movement of water, and moderate load. Water carrying large volumes of mechanical sediments rarely produces good sorting. Sorting is not well done by streams because of great current diversity, the maze of currents present at most points, and the small ratios between capacity and load which obtain during the times of maximum transportation.

In standing bodies of water, on the other hand, deposition may be often repeated and greatly prolonged. The loads, except about the mouths of

[117] Searle, A. B., op. cit., pp. 232–233.

[118] Shaw, E. W., Sorting in sedimentary rocks, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 925–932.

streams, are usually small, with the result that excellent sorting is possible, but not necessarily assured. Beach deposits may be excellently sorted, but such is frequently not the case, due to the wide range in competency which is there possible. These different competencies bring different materials at different times, and some beaches show parallel bands of various materials, consisting of plant matter, shells and shell fragments, and quartz, garnet, magnetite, and other sands.[119] The plant matter tends to be highest. It might be supposed that the magnetite would be lowest, but usually it tends to be higher than the sands of lower specific gravity. This is thought to be due to the fact that the incoming water has greater competency than the outgoing, so that the lighter sands are carried back and the heavier are left. The highest degree of sorting of fine sediments by water seems to occur in fresh-water lakes. The sorting of sediments deposited in salt water seems to be good, and clear separation of materials and sharp delimitation of beds commonly seems to obtain.[120] Sharp delimitation of beds may, however, occur in both salt and fresh water.

TRANSPORTATION AND DEPOSITION BY THE ATMOSPHERE

Transportation and deposition by the atmosphere are unique in that large portions of material are transported against gravity. Other agents generally leave the material transported at an elevation lower than that from which it was taken, but the materials transported by the currents of the atmosphere are as likely to be carried to places higher than the sources as to lower places. This increases the difficulty of relating an eolian sediment to its place of origin.

Wind velocities, because of the protection of trees and other objects, which produces retardation of currents, are lowest near the ground and tend to increase upward,[121] the rate of increase appearing to be very rapid. Hedin noted that a velocity of 40.5 miles an hour close to the ground would increase to nearly 60 miles per hour on the top of a mound 6 to 7 feet higher.[122] The wind velocity on the top of Eifel Tower, a little less than 1000 feet high, is four times that on the top of an adjoining tower 70 feet high.[123] This places the atmosphere at a disadvantage in that it has its least ability

[119] Kennedy, N. W., The natural panning of minerals in littoral deposits, Proc. Liverpool Geol. Soc., vol. 13, pt. iii, 1922, pp. 161–165.

[120] Kindle, E. M., Diagnostic characteristics of marine clastics, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 907–908; Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv. Canada, 1921, p. 37.

[121] Udden, J. A., Erosion, transportation, and sedimentation performed by the atmosphere, Jour. Geol., vol. 2, 1894, p. 320.

[122] Hedin, S. Central Asia and Tibet, 1903, p. 349.

[123] Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 25, 1914, p. 253.

to obtain a suspended load at the sources of supply. All materials must first be lifted through this stratum of lower velocity before they can be handled to the best advantage. It must not be assumed, however, that wind velocities near the ground are exceedingly low. The velocity given by Hedin of 40.5 miles per hour close to the ground would be competent to transport small pebbles in suspension, and the cutting down of telegraph poles in the western deserts indicates considerable velocity. Furthermore, the air near the ground is almost always in a labyrinthine turmoil, due to deflection from the many irregularities, and strong upward currents result which in many instances are competent to lift particles of sand dimension. Another fact of importance is the extremely rapid change in wind velocity which may take place over short intervals of time. The diagram below

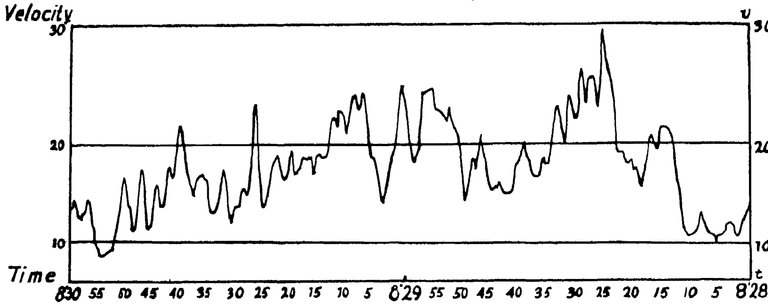

FIG. 4. CHANGES IN VELOCITY OF WIND DURING 2 MINUTES

The velocity is given in meters per second and the observations were made at Perpignan, France, on February 8, 1889, between 8:28 and 8:30 A.M. After Hann, J., Lehrbuch der Meteorologie, 2nd ed., 1906, p. 285.

(fig. 4), reproduced from Hann,[124] gives an excellent picture of the variations which may occur within two minutes.[111] Over extensive flat areas the air currents are comparatively steady at an elevation of about 200 meters, but in regions of great relief, with mountains projecting to great heights, the air is agitated to high elevations.[125]

Sources of the Load

The material transported by the atmosphere is derived from many sources. Over flat surfaces the stratum of low velocity near the ground limits the ability of the wind to obtain material; in dry areas this is accomplished to a considerable degree by upward currents and the many whirlwinds characteristic of such areas. Plant-covered surfaces contribute little other than organic material. Regions of seasonal dryness ranging to aridity make

[124] Hann, J., Lehrbuch der Meteorologie, 2nd ed., 1906, p. 285.
[125] Humphreys, W. J., Physics of the air, 1920, p. 123.

great contributions, particularly where there are variations in relief to favor concentration of the winds in hollows and on elevated places projecting upward through the stratum of low velocity. Flood plains of rivers quite commonly provide great volumes of material, an excellent illustration being the flood plain of the La Crosse River near Sparta, Wisconsin. This river deposits much silt and fine- to medium-grained sand westward from the town, and during strong westerly winds clouds of dust and fine sand are blown eastward up the valley. At the town the river changes its direction from southwestward to westward, so that the sand and dust are mostly carried up the valleys of Swamp and Silver creeks. During the Ice Age the work appears to have been more extensive than at present, as shown by the partially grassed-over dunes on the surfaces of these valleys. The sand is left in the valleys, but the dust rises to be deposited over the higher lands where the two creeks have their sources.

Mountains rising above the timber line lose all their fine material to the winds, and regions of high latitude free of vegetation or snow also have all fine material blown away. Cape Sand Top on the east end of Anticosti Island is a barren area over limestone which has been greatly shattered by frost action and from which the winds have removed all the fine material. The surfaces of glaciers and the deposits made where they melt yield much fine material to winds, and on sea and lake shores large quantities of sand and small shells are carried inland for long distances. Dry lakes of desert regions may have their clay and silt deposits broken up to fine particles by reason of the crystallization of salt, and thus occasionally yield considerable volumes of dust to the winds. Volcanoes are unique in that the materials contributed by them are driven into the higher currents of the atmosphere, and materials of cosmic origin enter the atmosphere from above. The quantity of the latter, however, is so small that its presence is not appreciable in atmospheric deposits. Animals on dry lands stir up great volumes of dust, Passarge having expressed the opinion that the chief agents of past erosion on some lands were the great herds of vertebrates there found, and that to them are due gently inclined plains free from river furrowing.[126] Man's different industries and activities are daily providing the atmosphere with enormous volumes of material, and his coal dust may be found in the geologic future in many deposits. His destruction of plant life, moreover, has increased the surface from which winds may obtain materials.

Methods and Distances of Transportation

The atmosphere transports material in suspension and by traction, that carried by the latter method consisting of coarse material of which the

[126] Passarge, S., Die pfannenförmigen Hohlformen der südafrikanischen Steppen, Petermann's Mitth., vol. 57, pt. ii, 1911, pp. 130–135.

greater part is sand. The materials transported in suspension are mostly clay and silt particles and very fine sand.

The distance of transportation by suspension varies with the dimensions. For a single lifting in moderately strong winds Udden's experiments gave results as follows:[127]

Materials and dimensions	*Distance of transportation*
Particles 1 to 8 mm. in diameter	a few feet
Coarse and medium sand, 1 to $\frac{1}{4}$ mm.	less than 1 mile
Very fine sand, $\frac{1}{16}$ to $\frac{1}{8}$ mm.	a few miles
Coarse silt, $\frac{1}{32}$ to $\frac{1}{16}$ mm.	200 miles
Medium silt, $\frac{1}{64}$ to $\frac{1}{32}$ mm.	1000 miles
Fine silt and clay particles up to $\frac{1}{64}$ mm.	around the globe

With repeated lifting the coarse material may also be transported long distances.

A dust fall which occurred March 9, 1918, over Wisconsin and adjacent states contained materials[128] which suggest that the place of origin was the semi-arid region of New Mexico, Arizona, and adjacent states, a distance of around 2000 miles. The dust from the great eruption of Krakatoa in 1883 is thought to have made the circuit of the globe before settling, and some of the dust is thought to have remained in the atmosphere for three years.[129] On the morning of April 27, 1928, with wind from the east, a yellow brown dust composed of fresh feldspar, magnetite, and augite fell over parts of Galicia, reaching a depth of 2 mm. on some areas by 2:00 p.m.[130] This dust must have traveled a long distance. Darwin records dust falling over 1600 miles' latitude in the middle Atlantic adjacent to Africa; it was abundant enough 1030 miles west of Cape Verde to produce a haze in the air and to discolor the water.[131] Thoulet[132] was of the opinion that a considerable part of the sediments of the deep bottoms of the sea was transported from the lands by winds.

[127] Udden, J. A., The mechanical composition of wind deposits, Augustana Library Publications, no. 1, 1898, p. 65.

[128] Winchell, A. N., and Miller, E. R., The dustfall of March 9, 1918, Am. Jour. Sci., vol. 46, 1918, pp. 599–609; The dustfalls of March, 1918, Monthly Weather Rev., vol. 46, 1918, pp. 502–506.

[129] Salisbury, R. D., Physiography, 1907, p. 57.

[130] Reck, H., Notiz über den osteuropäischen Staubfall Ende April, 1928, Centralbl. f. Min. etc., Abt. B., Nr. 10, 1928, pp. 521–524.

[131] Darwin, C., An account of the fine dust which often falls on vessels in the Atlantic Ocean, Quart. Jour. Geol. Soc., vol. 2, 1846, pp. 26–30.

[132] Thoulet, J., Origine éolienne des minéraux fins contenus dans les fonds marins, Compt. Rend., Acad. Sci., Paris, vol. 146, 1908, pp. 1346–1347; De l'influence du vent dans le remplissage du lit de l'océan, op. cit., pp. 1184–1186.

Competency, Capacity, and Load

The maximum dimensions of particles transported by traction are not great, but moderate winds may readily move grains a millimeter in diameter, while strong winds may move material the size of peas.[133] On rare occasions larger pebbles may be moved, Pumpelly noting that he saw stones 2 inches in diameter blown by a storm in Turkestan.[134] Blackwelder states that a windstorm on Rogers playa with a velocity of 40 miles an hour at a height of 5 feet above the ground (velocity measured with a Tycos anemometer) was rolling pebbles measuring from 5 to 10 mm. in diameter along a flat surface and the same wind threw pebbles 2 to 3 mm. in diameter into the automobile. In the same playa are giant ripple marks made by the wind with wave length of 8 to 10 feet, about 12 inches high, and composed of pebbles from 1 to 4 mm. in diamcter. In Coyote playa, northeast of Barstow, California, are giant wind ripples of larger size with pebbles ranging from 5 to 23 mm. in longest diameter and 4 to 10 mm. in shortest diameter.[135]

TABLE 15

VELOCITY OF WIND	MAXIMUM DIAMETER OF PARTICLE
meters per second	*mm.*
4.5–6.7	0.25
6.7–8.4	0.5
9.8–11.4	1.0
11.4–13.0	1.5

Experimental work by Udden[136] has shown that in winds of about 8 miles per hour the maximum size of material that can readily be transported in suspension is about 0.1 mm. The world-wide distribution of extremely fine material of volcanic origin proves, however, that material of such dimensions can be sustained for very long periods of time. Cressey[137] found that a velocity of 6.8 miles per hour is very close to that necessary to start sand movement, and Beadnell[138] states that sands on the dunes of the Libyan desert begin to move when the wind velocity reaches 13 miles an hour, and

[133] Walther, J., Das Gesetz der Wüstenbildung, 1900, p. 97.

[134] Pumpelly, R., Publ. 73, vol. 2, Carnegie Inst. Washington, 1908, p. 303.

[135] Blackwelder, E., Letter of Jan. 21, 1932.

[136] Udden, J. A., Erosion, transportation, and sedimentation by the atmosphere, Jour. Geol., vol. 2, 1894, p. 322.

[137] Cressey, G. B., The Indiana sand dunes and shore lines of the Lake Michigan Basin, Bull. 8, Geog. Soc. Chicago, 1928, p. 23.

[138] Beadnell, H. J. L., Sand dunes of the Libyan Desert, Geog. Jour., vol. 35, 1910, p. 386.

the air becomes visibly charged with sand when the velocity becomes 23 miles an hour. Experimentation with currents of known velocities yielded Sokolow the results given in table 15.[139] Thoulet[140] carried out similar experiments, with results as given in table 16. The particles used were quartz.

TABLE 16

VELOCITY OF WIND	DIAMETER OF PARTICLES TRANSPORTED
meters per second	*mm.*
0.50	0.04
1.00	0.08
2.00	0.16
3.00	0.25
4.00	0.33
5.00	0.41
6.00	0 49
7.00	0.57
8.00	0.65
9.00	0.73
10.00	0.81
11.00	0.89
12.00	0.97
13.00	1.05

TABLE 17

AVERAGE DIAMETER OF GRAINS	BEHAVIOR OF THE PARTICLES WHEN THROWN INTO THE AIR
mm.	
0.75	Diverged about 10 degrees from a vertical line
0.37	Diverged about 45 degrees from a vertical line
0.18	Diverged but a few degrees from a horizontal line, and was blown upward by eddies
0.08	Could scarcely be noticed to settle
0.04	Apparently completely borne up by the wind
0.007	Completely borne up by the wind
0.001	Completely borne up by the wind

Udden, experimenting with grains of determined diameters with the wind blowing about 8 miles per hour, obtained the results shown in table 17.[141]

[139] Sokolow, N. A., Die Dünen, Bildung, Entwickelung and innerer Bau, German transl. by A. Arzruni, Berlin, 1894.

[140] Thoulet, J., De l'influence du vent dans le remplissage du lit de l'océan, Compt. Rend. Acad. Sci. Paris, vol. 146, 1908, pp. 1184–1186.

[141] Udden, J. A., op. cit., 1894, p. 323.

Because of its low density, which at the earth's surface is only $\frac{1}{813}$ that of water, the capacity of a given volume of the atmosphere does not compare with that of an equal volume of water. As both capacity and competency of each are so largely conditioned by velocity, and the atmospheric currents attain far greater velocities than water currents, it follows, that, dependent upon varying conditions of temperature, density, and viscosity, there are certain velocities of the atmosphere and water at which the capacities are equal. According to Rubey, this is the case for particles greater than 0.2 mm. in diameter when the velocity of the air is thirty-six times that of water, and the ratio is greater for smaller particles.[142] Due to its great volume the atmosphere has enormous capacity. Udden,[143] comparing the carrying power of the atmosphere over the Mississippi Valley with that of the Mississippi River system, came to the conclusion that the capacity of the former is one thousand times as great as that of the latter, although a given quantity of water with a given velocity is able to carry many times as much as an equal volume of air with the same velocity.

Except for limited occurrences, the load actually carried by any portion of the atmosphere is only a fraction of its capacity. The quantity which is known to be occasionally transported is very great. The dust fall on March 9, 1918, affecting Wisconsin and adjacent states, transported to these states at least a million tons of material,[144] and that of March 19, 1920, brought fully twice as much.[145] The noticeable falls ordinarily are due to exceptional conditions, but large quantities are falling all the time, as the dust penetrating everywhere shows, and the quantity in the atmosphere at any one time must be very great. Udden[146] has stated that on the average 850,000,000 tons of dust are carried in the Mississippi Valley 1440 miles each year, and according to Free,[147] portions of the surface of Europe have received dust removed from the Sahara to the depth of $5\frac{1}{2}$ inches during the 3000 years of which there are anything like records. While he considers this figure too high for northern Germany and England, it is considered too low for Italy, southern France, and the Tirol. According to Petrie, 8 feet of material have been removed by wind from the Nile delta in the past

[142] Rubey, W. W., Letter of July 18, 1932.

[143] Udden, J. A., op. cit., 1894, p. 327.

[144] Winchell and Miller, op. cit., p. 605.

[145] Winchell, A. N., The great dustfall of 1920, Am. Jour. Sci., vol. 3, 1920, pp. 349–364. See also Dove, L. P., The dust storm of January 1921, Quart. Jour. Univ. North Dakota, 1921, pp. 248–250, where a fall of 801 tons per square mile is indicated.

[146] Udden, J. A., Dust and sand storms in the West, Pop. Sci. Monthly, vol. 49, 1896, pp. 655–664.

[147] Free, E. E., The movement of soil material by the wind, Bull. 68, U. S. Bureau of Soils, 1917, p. 99. The work contains an extensive bibliography on wind work.

2600 years.[148] The great effects of deflation in the arid southwest of the United States have been shown by Blackwelder[149] and others, the former having stated that 14 or more feet have been removed from the Danby Dry Lake of southern California. The fact that sand storms of a week in the desert region of Nevada may destroy the transparency of the wind shield of an automobile proves that wind provided with sand may obtain considerable material from solid rock.

The patient work of Aitkin[150] has demonstrated that dust particles are present at all times in the lower parts of the atmosphere. Observations made by him showed for 1890 at 16 separate stations an average of 1562.9 particles of dust for each cubic centimeter, with the lowest, 16, at Kingairlock, Scotland, and the highest, 26,000, at Mentone, France. In 1891, with 297 places of observation, the average number of particles per cubic centimeter was 1475.8 with the highest, 40,000, at Milan, Italy, and the lowest, 43, again at Kingairlock. In 1893 there were two days in Milan when the numbers were 100,000 and 150,000 respectively.

The load of sand transported in arid countries by winds of high velocities is often very large. Hedin has stated that in Central Asia "inconceivable quantities of sand and dust" are transported to the south and southwest, and that the suspended sand at times was so thick that a real "sand fog" existed, through which it was impossible to see anything very short distances away.[151] Dust storms are said to have occurred in the region of the town of Post in northwest Texas during which the air was so filled as to render houses across a street invisible.

What has been said applies only to the material transported in suspension. In addition, there are vast quantities rolled on the ground to make the sand dunes of lake and sea shores, arid regions, and the valleys of some rivers. Lesser quantities are rolled in regions which are subject to seasonal dryness. The sands so rolled are relatively free from finer grains, but contain particles of larger dimensions within the range of the competency of the transporting wind and as determined by dimensions at the sources of supply. This is explained by Udden[152] as follows:

[148] Petrie, W. M. F., Wind action in Egypt, Proc. Roy. Geog. Soc., vol. 11, 1889, pp. 646–650.

[149] Blackwelder, E., The lowering of playas by deflation, Am. Jour. Sci., vol. 21, 1931, pp. 140–144.

[150] Aitkin, J., On the number of dust particles in the atmosphere of certain places in Great Britain and the continent, with remarks on the relation between the amount of dust and meteorological phenomena, Trans. Roy. Soc. Edinburgh, vol. 35, 1890, pp. 1–19; vol. 37, 1895, pp. 17–50, 621–639.

[151] Hedin, S., Central Asia and Tibet, vol. 1, 1903, pp. 346–350.

[152] Udden, J. A., Augustana Library Publ., no. 1, 1898, pp. 24–25.

Materials finer than dune sand are wholly lifted up into swifter currents, which promptly remove them. The dune sand itself, on the other hand, is partly lifted and also partly rolled, just as the grains of the nearest larger sizes. Working in this last manner the transporting power of the wind varies more nearly in approximation to its erosive force than to its lifting force. With changes in velocities the latter varies as the sixth power, while the erosive force varies as the square. It is, therefore, much easier for the coarser ingredients to be rolled along with the dune sand than it is for the dune sand to be picked up and carried away with the finer ingredients.

Dake[153] stated this principle thus: "If the total coarser than the maximum grade is greater than the total finer than the maximum grade, the sand is more probably eolian." The principle is not, however, of exclusive application, as water may produce a sand of similar sorting.

Character and Dimensions of the Material Transported

Areas whose rocks are undergoing disintegration rather than decomposition are probably the largest contributors to the materials transported by the atmosphere. The Madison dust fall of March 9, 1918, had its materials "dominantly composed of feldspar and quartz with very small amounts of other constituents. Kaolin was not abundant and the feldspars were entirely unaltered."[154] The material contained some vegetable matter and also some diatoms. A complex mineral composition would seem to be the rule.

The larger particles which are rolled on the ground consist mostly of quartz, but locally calcareous matter is the composing material. Sands of gypsum[155] also occur, and dunes of clay have been described.[156] The dune sands of northern Indiana[157] seem to contain few heavy minerals, and soft materials do not seem to be common. Rarity of heavy minerals cannot, however, be stated to be a characteristic of eolian deposits, but may as well be interpreted as due to scarcity of such in the source of supply. Absence of soft minerals, on the other hand, may be due to long transportation or to rarity of these minerals at the places where winds obtain their materials.

The material of the Madison dust shower contained shells of diatoms. The number was small, but the occurrence of such minute organisms should be expected in essentially all deposits to which the wind might add constituents. Materials transported inland from the seashore not uncommonly contain

[153] Dake, C. L., The problem of the St. Peter sandstone, Bull. Univ. Missouri, vol. 6, no. 1, 1921, p. 173.

[154] Winchell and Miller, op. cit., p. 607.

[155] Herrick, C. L., The geology of the white sands of New Mexico, Jour. Geol., vol. 8, 1900, pp. 112–128.

[156] Coffey, G. N., Dunes of clay, Jour. Geol., vol. 17, 1909, pp. 754–755.

[157] Cressey, G. B., op. cit., 1928, pp. 32–33.

shells of marine organisms. Such occur, for example, in the sands which are blown inland from the shores of the Bermudas;[158] and on the coast of Galway, Ireland, there are dunes which are composed almost wholly of the shells of Miliolinæ and *Truncatulina*.[158] Evans[159] gives several examples of ancient limestones which appear to be of atmospheric deposition and which contain many shells of marine animals, and Grabau suggests that the chalk may have been of such deposition. Such transportation of small marine shells long distances inland brings them into an environment to which they are not native and where their presence in deposits suggests a marine origin for the latter. Material of marine organic production is thus not always deposited by marine agencies. Oolites are forming in Great Salt Lake and in the waters about portions of the Florida coast; they are thrown on the shores by waves and carried inland by the winds—a product of marine production and eolian deposition. Grabau[160] states that Jurassic oolitic limestones of Great Britain have cross-lamination suggestive of eolian deposition, and Evans[161] had previously expressed a similar opinion for these cross-laminated limestones.

The sizes of the grains of the Madison dustfall of 1918 were small, ranging from 0.005 to 1 mm.; 85 per cent had dimensions of 0.005 to 0.025 mm.; and 56.17 per cent had dimensions of 0.01 to 0.025 mm. Udden's many analyses show that for wind-transported dust the dimensions mainly fall between $\frac{1}{64}$ and · mm.

Sorting and Rounding by the Atmosphere

Sorting of the materials carried by the atmosphere may reach a high degree of perfection. The large ratio between capacity and load makes the distances between particles of such dimensions that they ordinarily are independent of each other, and the grains deposited by a current of any given velocity are likely to be of approximately equal dimensions. However, the atmosphere is not a river confined to a definite channel and moving in a very definite direction, but is a mesh of conflicting cross currents,[162] up, down, and lateral. This criss-crossing of currents of different load and velocity leads to a mixing of materials of different dimensions, so that within a given

[158] Grabau, A. W., Principles of stratigraphy, 1911, p. 573.

[159] Evans, J. W., Mechanically formed limestones from Junagarth (Kathiawar) and other localities, Quart. Jour. Geol. Soc., vol. 56, 1900, pp. 569–583, 588–589.

[160] Grabau, A. W., op. cit., p. 577.

[161] Evans, J. W., op. cit., p. 580.

[162] Langley, S. P., Internal work of the wind, Smithsonian Contrib. to Knowledge, vol. 27, no. 884, 1893. Also in Am. Jour. Sci., vol. 47, 1894, pp. 41–63.

space of atmosphere of a few hundred cubic feet there may be a wide range in dimension of materials, which Udden suggested might be comprehended between the numbers 1 to 100.[163] Udden[164] further suggested that sorting by wind was such that the second larger grade would be found on the coarser side of the maximum. It is to be noted that water currents can produce the same type of sorting.[165]

The material rolled on the ground in a current of certain velocity may be well sorted, but the very fact of nearness to the ground leads to great variation in current velocity from place to place and to deflections of currents of different velocity into one another. This is splendidly shown where snow or sand is drifting on ice. Udden's tables give the range in dimensions of dune sands from $\frac{1}{16}$ mm. to 1 mm., with over 80 per cent of the material falling between $\frac{1}{8}$ and $\frac{1}{2}$ mm.

Material suspended in the atmosphere has the grains ordinarily so far apart that the particles in any one current are not likely to affect each other, but in a maze of criss-crossing currents there may be many collisions and considerable abrasion, so that the grains may become rounded to very small dimensions, it having been noted by Sauer[166] and Früh[167] that even very fine grains of loess may be well rounded. From experimental work Ziegler[168] concluded that if grains are rounded to less than 0.75 mm. the work must have been done by the wind, but experiments by Galloway indicated that water may round particles to dimensions as small as 0.05 mm., and wind to 0.03 mm.[169] On subsequent pages there will be pointed out ways in which rounding may be accomplished to small dimensions when wind is not the agent. The material rolled on the ground is almost constantly in contact with something or other, and the grains generally become well rounded if transported sufficiently long. The constant impact of grain on grain produces ground glass or mat surfaces, and unless these are modified by solution the feature is retained. If subjected to solution sufficiently long, the mat

[163] Udden, J. A., Erosion, transportation, and sedimentation by the atmosphere, Jour. Geol., vol. 2, 1894, p. 328.

[164] Udden, J. A., Augustana Library Publ., no. 1, 1898, pp. 24–25.

[165] Dake, C. L., The problem of the St. Peter sandstone, Bull. Univ. Missouri, vol. 6, no. 1, 1921, pp. 142–145.

[166] Sauer, A., Über die äolische Entstehung der Löss am Rande der norddeutschen Tiefebene, Zeitschr. Naturwiss., Bd. 62, 1889, pp. 326–351.

[167] Früh, J., Der postglaciale Löss im St. Gallen Rheinthal mit Berücksichtigung der Lössfrage im allgemeinen, Vierteljahrschr. d. naturf. Gesells. in Zurich, vol. 44, 1899, pp. 157–191.

[168] Ziegler, V., Factors influencing the rounding of sand grains, Jour. Geol., vol. 19, 1911, pp. 645–654.

[169] Galloway, J. J., Private communication, June 29, 1923.

surface is lost and the grains become shiny and glassy.[170] Mackie[171] has formulated the following formula for the rounding, R, of grains of sand:

$$R \text{ varies as } \frac{\text{size} \times \text{specific gravity} \times \text{distance}}{\text{hardness}}$$

For a cube this becomes

$$R \text{ varies as } \frac{L^3 \times \text{S.G.} \times \dfrac{d}{4L}}{h} \text{ or } \frac{L^2 \times \text{S.G.} \times d}{4h}$$

where L equals the length of one side. For material transported by the atmosphere the distance traveled is usually relatively great, and the specific gravity of the substance is not diminished as is the case for minerals suspended in a liquid. Rounding may thus develop to a high degree of perfection.

Deposits made by wind do not always have well rounded particles. The particles may have been produced by agents other than the wind, and the latter may merely have been the agent of deposition. This is illustrated by dune sands near Sparta, Wisconsin, where the sands were derived from the water-deposited Cambrian sandstones and transported for some time by glacial ice. The melt waters spread the sands over the flood plain of the La Crosse River, whence the wind carried them a few miles east to their present locations. While wind-deposited, the grains show little indication of such in their characteristics. On the other hand, water may rework wind-produced sands, with the result that structures of water deposition and grains of wind production exist together.

The effects produced on the objects with which the material carried by the atmosphere comes in contact may be divided on the basis of whether the objects are fixed or movable. On the former are made the groove-like hollows (yardangs)[172] cut on flat clay surfaces, the mushroom-like rocks and etched surfaces characteristic of regions of wind erosion, and caves with undecomposed walls. Small movable stones in the path of wind-driven sand are cut, thereby leading to the development of facets (ventifacts, dreikanter, einkanter, windkanter)[173] (fig. 5). These facets have pitted and

[170] Galloway, J. J., Value of the physical characters of sand grains in the interpretation of the origin of sandstones, Bull. Geol. Soc. Am., vol. 33, 1922, p. 104.

[171] Mackie, W., On the laws that govern the rounding of particles of sand, Trans. Edinburgh Geol. Soc., vol. 7, 1897, pp. 298–311. Also Goodchild, J. H., Desert conditions in Britain, Ibid., vol. 7, 1897, pp. 203–222.

[172] Hedin, S., Central Asia and Tibet, 1903, p. 365.

[173] For bibliography see Bryan, K., Rept. Comm. Sed., Nat. Research Council, 1931, pp. 29–50.

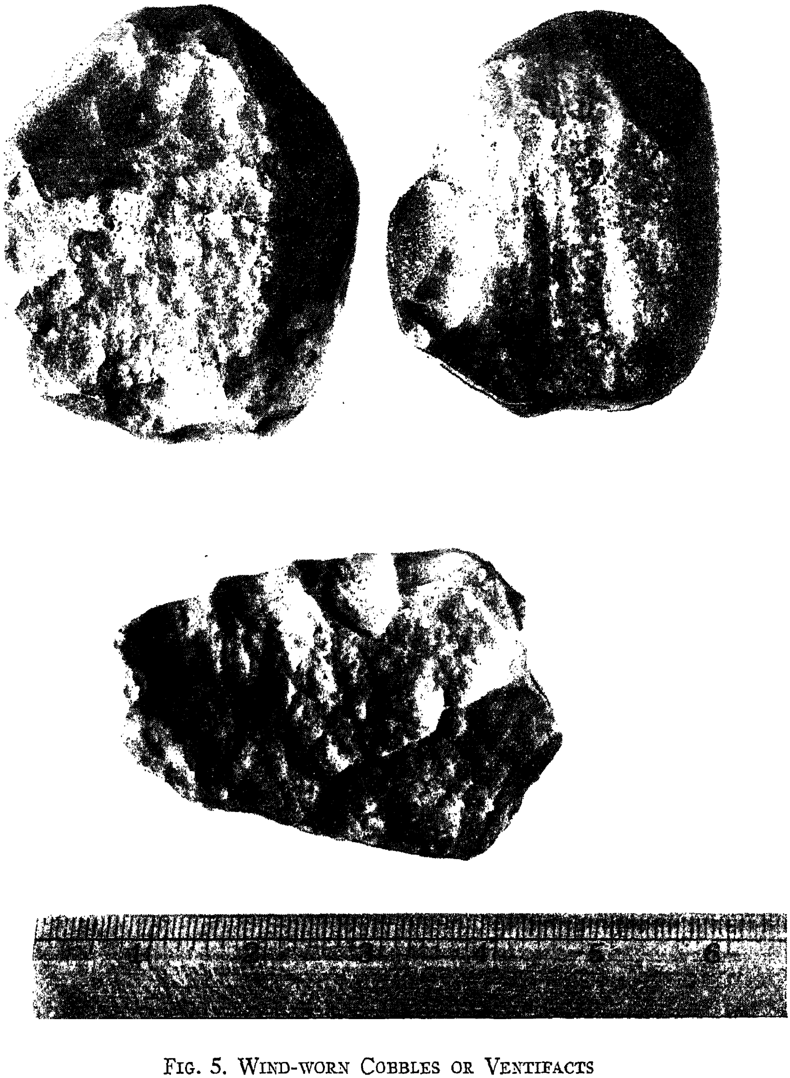

FIG. 5. WIND-WORN COBBLES OR VENTIFACTS

These cobbles show the effects of the impact of sand on hard rocks, the two in the upper part of the photograph being quartzite and the one below flint. The facets are numerous and all seem to have concave surfaces. Wind-worn particles are also known as dreikanter and einkanter. Collected in the desert region of the northwestern United States by Eliot Blackwelder. Photograph by Diemer, University of Wisconsin. The scale is in inches.

polished surfaces. It should be noted that facetted rock particles may also be produced by water[174] and ice, in the former case pitted, in the latter not. Another feature which is partly due to wind action is the desert "varnish" common in semi-arid regions, seemingly produced by capillary action which brings material from the interiors of rocks to the surface and by the polishing of this surface by wind-carried particles.[175] Laudermilk[176] considers that lichens have assisted by means of acid secretions which dissolved from the rock the manganese and iron oxides to which the "varnish" is so commonly due. It is a mistake, however, to assume that desert "varnish" is limited to desert and semi-arid regions as it seems to form in any region of seasonal dryness.

Causes and Places of Deposition

Deposition from the atmosphere, for most of the material, results from a lessening of wind velocity. It is possible that in some instances coarser materials are replaced by finer without any decrease in velocity. The coarser material falls first, followed by the finer. Material of colloidal and near-colloidal dimensions remains in suspension until brought down by snow, hail, or rain. Decrease in velocity leads progressively to deposition of the material carried by traction, the coarsest stopping first.

The material transported by traction is deposited not very great distances from, but leeward of, the places of origin. The places of deposition of the material carried in suspension depend upon whether this material is carried in the upper or lower currents. That which is carried in the lower currents may travel many miles to the leeward of the places of origin, and it is probable that the distances ultimately attained may reach hundreds of miles. The material transported in the upper currents of the atmosphere is very fine, settles very slowly, and hence travels extremely long distances. Sandstorms in the Grand Canyon country leave dust in the air in such quantities as to give it a brick-red color for several days,[177] and in the Sahara, Passarge states that clouds of reddish fine sand and dust remain a long time in the air,[178] gradually settling over the desert sands. Dust is transported and deposited to a greater or less degree over the entire earth, and, as has been pointed out, it is not unlikely that every square mile of the earth's surface contains dust from every other square mile.[179] Much must also be deposited in

[174] Gregory, H. E., Notes on the shapes of pebbles, Am. Jour. Sci., vol. 39, 1915, p. 302.

[175] Evans, J. W., The wearing down of the rocks, Proc. Geologists' Assoc., vol. 25, 1914, pp. 258–261.

[176] Laudermilk, J. D., On the origin of desert varnish, Am. Jour. Sci., vol. 21, 1931, pp. 51–66.

[177] Kolb, E. and Kolb, E., Nat. Geog. Mag., vol. 26, 1914, p. 134.

[178] Passarge, S., Grundzüge der Geologie, 1924, p. 669.

[179] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, 1906, p. 23.

waters of the ocean far from land, and the rate may be comparatively rapid. Material carried in suspension is deposited in more moist regions leeward of those of origin. Parts are deposited on higher lands leeward of the region of supply, as is now actually taking place with the dusts which are blown up the La Crosse River valley. During the Pleistocene the dust blown from the ice surface and the outwash fans and elsewhere settled over the warmer and more moist surfaces south of the ice sheets, probably in greatest thickness over those parts of the surface where the conditions were such as to check the wind's velocity or lead to the development of conflicting eddies, as the hollows in the hills or high ridges transverse to the direction of the winds, conditions which Willis noted are responsible in China for the deposition of wind-transported dust.[180]

Volcanic dusts and "sands" are deposited in largest quantities around the craters of origin, particularly the coarser constituents, but large quantities of the finer materials are carried leeward long distances, as is shown by the dust from the eruption of Krakatoa, which traveled entirely around the world, and the beds of volcanic ash in the Plains Tertiary of Kansas, Nebraska, and other western states.

Rates of Deposition and Thickness and Extent of Deposits

It seems probable that the rates of deposition for suspended materials are greater for dust of volcanic origin than for any other. On some occasions this has been so rapid as to cause great destruction of life. The fall of dust connected with the 1912 eruption of Mt. Katmai on the Alaska Peninsula produced an almost complete destruction of vegetation over extensive areas, small forms of land life—birds, rabbits, etc.—dying in large numbers, and even large forms being injured. Mosquitoes were practically exterminated over large areas. Even marine animals and plants, such as barnacles, mussels, and kelp, were killed. Within a matter of forty to sixty hours, dust settled to a thickness of 50 inches or more at distances as great as 10 miles from the crater, with decreasing thicknesses to 1 inch at a distance from 100 to 200 miles away. The great eruption in 1815 of Tomboro on the Island of Sumbawa led to the rapid deposition of ash to a thickness of 2 feet more than 850 miles from the mountain.[181]

An ancient example of the rapid settling of volcanic dust is registered in the Oligocene Florissant deposits of Colorado, where around 40 feet of volcanic ash occur. This probably represents several falls, and in falling, the ash

[180] Willis, B., Research in China, Publ. 54, Carnegie Inst. of Washington, vol. 1, pt. i, 1907, p. 186.

[181] Martin, G. C., The recent eruption of Katmai volcano, Nat. Geog. Mag., vol. 24, 1913, pp. 131–180.

carried down with it flies, ants, bees, spiders, butterflies, etc., together with many leaves, many of which are now preserved in wonderful perfection.[182]

The thickness of volcanic dust and "sand" deposits is commonly measured in tens of feet or less, but may rise to several hundred and even a thousand feet in the vicinity of the volcano from which they come. However, a great deal of the material in the vicinity of the source may hardly be classed as sediments. With distance from the volcano the materials become more truly sediments, and the thickness is not so great. Thus, the beds of volcanic ash in the Tertiary of Kansas, Oklahoma, and Nebraska have a maximum thickness around 25 feet, while a bed of volcanic ash in the Wind River Basin of Wyoming has a thickness of 13 feet.[183]

Dust derived from the surface is probably never in the atmosphere at any time in such large quantities as to be rapidly deposited in beds of a very great thickness, but as the deposition extends over immense periods of time, the ultimate thickness of the deposits is likely to be much greater for dust of this origin than for volcanic dust. Thus, the loess of the central portion of the United States reaches in places thicknesses exceeding 100 feet, and thicknesses of over 300 feet are said to obtain in China. Ordinarily the deposit of any year appears to be too thin to form a lamination, and as each year's deposit to some degree is worked into preceding deposits by rain, frost, and organisms, it follows that dust deposits made by wind are ordinarily without bedding.

In very strong winds of desert areas the sands ordinarily transported by traction are lifted from the ground, producing sand storms which may be seen for long distances as dense clouds and are the dread of the desert travelers.[184] The sand is driven at great velocities and settles in large quantities wherever the velocity is checked. Every traveler in arid and semi-arid regions probably has had the experience of having all his belongings filled with sand deposited from occasional sand storms. Another characteristic of arid regions is the common occurrence of whirlwinds, raising tall cylinders of dust and sand, which are rapidly deposited with each obstacle checking the velocity of the whirling wind. The thickness of any one deposit is as a rule small.

The sand transported by traction generally moves in the form of dunes which range in height from mere ripples to more than 200 feet, reaching 300 feet marginal to the Bay of Biscay and about twice that height on the coast

[182] Scudder, S. H., The Tertiary lake-basin at Florissant, Colorado, etc., U. S. Geol. and Geog. Surv. Terr., Bull. 6, 1882, pp. 279–300; Tertiary insects of North America, U. S. Geol. Surv. Terr., vol. 13, 1890, pp. 17–38.

[183] Sinclair, W. J., and Granger, W., Eocene and Oligocene of the Wind River and Big Horn basins, Bull. Am. Mus. Nat. Hist., vol. 30, 1911, pp. 83–117.

[184] Hedin, S., op. cit., p. 346.

of North Africa.[185] As these dunes advance, there is deposited rapidly, but very locally, a thickness of sand equal to the height of the dune. Since dunes advance slowly, the rate on the Bay of Biscay ranging from 15 to 105 feet per year and in most other dune regions approximating these figures, although it may rise to as much as several miles per year, it is obvious that the area covered by thick deposits does not, in general, increase very rapidly. The total thickness which accumulates, however, may be very great. A great dune area lies adjacent to the Caspian Sea, the sand originally coming from deposits made on the flood plains of the Oxus and Jaxertes rivers. As the flood plains dry up, the winds carry away the dust, and the sand is piled up into dunes, which for the Jaxartes River migrate southward across the Kizil Kum desert at a rate which may be as great as 20 meters (65 feet) on a stormy day, the average being 6 meters per day. As the Amudarja (Oxus) lies in the path of the dunes coming from the Jaxertes, the sands are given to the former river, which deposits a part of them on its flood plain, whence they are again taken by the wind and drifted southward across the Transcaucasian or Kara Kum desert to the borders of the Caspian Sea. This migration had led and still leads to an annual increment of wind-deposited sand which ultimately will reach a great thickness.[186]

Deposits of the atmosphere attain great extent. In the Sahara one-ninth of its area, about 380,000 square miles, is covered with dunes, there are about 320,000 square miles of dune area in Arabia,[187] and extensive dune areas exist in central Asia, central Australia, and western United States. There are further large areas in Mexico and parts of South America, and smaller areas occur on sea, lake, and river shores of many parts of the world, so it is probable that atmospheric traction deposits are now forming over about a million square miles of the present land surface. Atmospheric dust deposits of significant thickness, the loess, cover tens of thousands of square miles in China, North Europe, and the United States. Nevertheless, loess does not seem to be common in the geologic column, although the latter shows extensive eolian sand deposits in the rocks of several periods. It is not unlikely that eolian sands and dusts were deposited over extensive areas during every period. In the early ages, before vegetation developed to protect the surface, there must have been vast areas covered by drifting sands; sands of eolian production should have been abundant, and there should be extensive deposits of atmosphere-transported dust. Some of these atmospheric deposits must have been preserved, but they do not appear to have been found.

[185] Grabau, A. W., Comprehensive geology, vol. 1, 1920, p. 446.
[186] Walther, J., Das Gesetz der Wüstenbildung, 2nd. ed., 1912, p. 259.
[187] Grabau, A. W., Comprehensive geology, vol. 1, 1920, p. 450.

Characteristics of Wind Deposits

SIZE OF GRAIN. Under the heading of competency an examination was made as to the sizes of grains that are known to have been transported by the wind. Under the present heading the matter is examined from the point of view of the sizes of grains found in wind deposits. According to Sokolow,[188] there are no wind deposits known of which the grains exceed 4 or 5 mm. in diameter, while the average dimension is less than 1 mm. In the Libyan desert the range is from 0.5 to 2 mm.[189] Sands from Pleistocene dunes on the Camp Robinson Military Reservation near Sparta, Wisconsin, have dimensions ranging from about 0.2 to 0.6 mm., with very small percentages above and below those limits. Deposits of suspended materials range downward to almost infinite fineness.

The sands deposited on opposite sides of dunes vary in dimension and those of both sides differ in the same respect from the sands deposited in the depressions between the dunes. The sands which compose the windward sides are coarser than those on the leeward, due to the fact that the lighter and smaller have been blown away and the larger and heavier left. The average dimensions of the sand in the main body of a dune fall between $\frac{1}{8}$ and 1 mm., and the dimensions of over 90 per cent fall between these figures. The average dimensions of the lee sands (sands on the leeward sides of dunes) fall between $\frac{1}{16}$ and $\frac{1}{2}$ mm. The coarser materials which are left after most of the fine stuff is blown away constitute what Udden has called the lag gravels,[190] and with these larger particles may be a few smaller ones, retained because of the protection afforded by the former. The dimensions of the lag gravels do not fall into so compact a group as is characteristic of the materials of the dune, and their curve is flatter and more irregular. A lag gravel curve is likely to have more than one maximum, and Udden's analyses show that the dimensions fall between $\frac{1}{8}$ and 8 mm. His maximum dimension is, however, several times too small and there are many lag gravels over the arid regions of the Southwest which are several inches in dimension and which reached their present positions by stream action or release from underlying rock. Lag gravels may thoroughly cloak those surfaces from which the sands and dusts have been removed. They are usually more or less angular and wind-worn and covered with desert varnish. They cover large areas of deserts and their presence serves as a

[188] Sokolow, N. A., Die Dünen, Bildung, Entwickelung und innerer Bau, German transl. by A. Arzruni, Berlin, 1894.

[189] Grabau, A. W., Principles of stratigraphy, 1913, p. 553.

[190] Udden, J. A., Mechanical composition of wind deposits, Augustana Library Publ., No. 1, 1898.

protection for the finer materials beneath and among them and slows up removal of such.[191]

SPHERICITY AND FROSTING OF WIND-DEPOSITED SANDS. As previously noted, winds are probably able to produce rounded grains of smaller dimensions than ordinarily is possible in water. The striking of grain on grain gives a frosted or ground glass surface, a feature also developed on larger water-formed particles. However, many sand grains deposited from the atmosphere are little rounded or frosted, and in many instances sand grains of wind production are given to water and deposited thereby, so that precautions are necessary in using these characteristics in interpretation. Cressey's[192] studies indicated a higher degree of rounding of the dune sands of northern Indiana than of the sands of the adjacent beaches, but the differences seem too little to be significant.

CONTEMPORANEOUS STRUCTURES IN DEPOSITS MADE BY THE ATMOSPHERE. As has been noted, the deposits made from suspension are commonly without stratification. Such stratification as does occur is parallel to the surface receiving the deposits. Most of the material transported by traction moves as dunes, in which the sands move up the windward side and roll down the leeward side. Cross-lamination is developed on the leeward side, the material of each lamination representing the deposit made by wind of a certain velocity, and differing from the material of laminations above and below in dimension of grain, but usually not in composition. The laminations have inclinations approximating the angle of repose of the composing sands. The angles of repose for various substances in different media have been investigated by Thoulet, Le Blanc, and others.[193] Thoulet's conclusions were stated as a number of laws, which expressed in formula give the following:

Slope or angle varies as

$$\frac{dm\ (dm - dl) \times c \times r}{dl \times s \times ag \times d},$$

where dm is the density of the material, dl the density of the medium, d the dimension of the particle, s the sphericity, ag the agitation of the medium, c the cohesion, and r the rate of deposition. The angle of inclination according to Thoulet never exceeds 41 degrees. Passarge[194] states that the slopes of the lee sides of dunes, and thus the inclinations of the cross-lami-

[191] Passarge, S., Grundzüge der Geologie, 1924, p. 668.

[192] Cressey, G. B., The Indiana sand dunes and shore lines of the Lake Michigan Basin, Geog. Soc. Chicago, Bull. 8, 1928, p. 3.

[193] Thoulet, J., Étude expérimentale et considérations générales sur l'inclination des talus de matières meubles, Ann. Chim. et Phys., vol. 12, 1887, pp. 33–64.

[194] Passarge, S., op. cit., p. 671.

nations, range from 30 to 33 degrees. The lee slopes are given a range of 5 to 12 degrees. Cressey[195] found that the maximum angle of eolian cross-lamination in the Indiana dunes is not steeper than 32 degrees.

The fact that wind-transported sands ordinarily are well rounded tends to lower the angle of inclination; the low density of the air favors high inclination; and the rapid deposition taking place in dunes works toward the same end. The deposits tend to have the coarser material at the bottom, as large fragments usually roll farther before momentum is overcome, but as most particles in a dune are small, differences of momentum have little effect. Inclinations are apt to be higher at the upper ends of the laminations than at the bases, as any agitation of the medium tends to remove material from the top to the base, and there may be spreading of the basal materials due to the weight of the overlying ones. As a general proposition it does not seem probable that angles of inclination of wind deposits are greatly different from those made in water.

As wind currents vary constantly in direction and velocity, truncation of laminations is more or less continually taking place, and the varying directions and velocities of the winds lead to great variations in degree and direction of the angles of inclination. The planes of truncation are not as a rule horizontal or parallel, so that in most instances each unit of cross-lamination is wedge-shaped in cross section. It is this characteristic—wedge-shaped, cross-laminated units with the laminations of the several units inclined in many directions—that distinguishes wind-deposited sands from those deposited by water, but care needs to be exercised in application of this criterion, as water-deposited sands for limited extents may show similar characteristics.

Wind develops ripple marks on the sand over which it blows. These ripples are not symmetrical and have a ripple index which is usually greater than 15. In cross section they show as small asymmetrical wrinkles. Wind ripple-mark is not likely to be preserved.

Color. Colors of wind-deposited sediments depend upon the climates of the regions of deposition, the rates of deposition, the vigor and extent of transportation, and the colors of the parent rocks. Common colors are white to yellow. The dusts after deposition seem to be mostly yellow, but, as noted, there are red dusts in southwestern United States and in the Sahara. Dune sands of lateritic materials occasionally occur in tropical regions and in the Sahara Desert. A light reddish color is in places given to the dune surfaces on account of the settling of a reddish dust.[196]

[195] Cressey, G. B., op. cit., p. 37.
[196] Passarge, S., op. cit., p. 671.

Summary of Characteristics of Atmospheric Deposits

Wind deposits are comparatively well sorted, and particles of sand dimension usually are well rounded, minutely pitted, and frosted. Coarse deposits are cross-laminated, with the lamination planes at high angles and in many directions. The planes of division between cross-laminated units are usually not parallel to each other or horizontal. Fine deposits ordinarily are without lamination.

The materials of wind deposits may come from immense distances; much of them may be unweathered; and the fine materials are deposited everywhere, so that some occur in the deposits made in every environment and thus may be responsible for rare constituents in any deposit. Locally materials of wind transportation make important contributions to the loads of other transporting agents. Colors are white to yellow, and in tropical climates some eolian deposits may be red. The sands are mostly quartz. The fine materials are mixtures of everything.

TRANSPORTATION AND DEPOSITION BY ICE

The billions of tons of drift spread over the surface of parts of the northern hemisphere emphasize the work done by glacial ice in the formation of sedimentary deposits. Transportation by this agent can take place on very gentle slopes, and for a space materials may be moved uphill; but uphill transportation is of very local extent, and for most of the material transported the place of deposition is lower than the place of origin. Other ice transportation and deposition are done in the sea, lakes, and rivers.

Transportation and Deposition by Glacial Ice

Sources of Load. The material transported and ultimately deposited by glacial ice is either derived from the loose material previously mantling the surface or is plucked, filed, or rasped from the solid rock beneath. Large volumes of the loads of mountain glaciers fall or slide from the cliffs and slopes at the feet of which the glaciers move.

Methods of Carrying Load. The material transported by glacial ice is carried on the surface, within the body of the ice, and beneath the ice. The methods of transportation are entirely physical. Much and perhaps most of the material is solidly frozen in the ice, so that a glacier may be likened to a conglomerate or breccia in motion, the matrix being ice and the pebbles composed of rock from many sources. With increase in the volume of the material carried as compared to the matrix, the difficulty of transportation increases and the rate approaches zero as a limit. Ultimately a point

may be reached where that portion of the glacier having a larger proportion of matrix may find it easier to override the part filled with rock than to push it, and the latter is left behind.

Distance of Transportation. The distance to which material may be transported by glacial ice is limited only by the distance the ice travels, but it appears quite generally true that most of the material which was deposited by the Pleistocene and other ice sheets was derived from only a few tens or at most a few hundreds of miles back from the places of deposition. On the other hand, some of the material is known to have come many hundreds of miles. Where glaciers reach bodies of water, portions break away as icebergs, on which some of the load may be carried to lower latitudes. The loads are scattered over the paths of travel and thus may become incorporated in sediments of other character and origin. Under existing climatic conditions the bergs may travel several thousand miles before melting occurs, so that glacier boulders are now being spread over wide areas of the sea bottom. Rock fragments of this origin may be expected, therefore, in the marine and lake sediments of several of the geologic periods.

Competency, Capacity, and Load. The competency of glacial ice to transport material has essentially no limit. It is the one agent of transportation which is able to transport blocks weighing thousands and perhaps millions of tons. The capacity to transport is also great. If the burden lies near the base of the ice, transportation is difficult, but so long as the burden is on top of, or within, the ice, there appears to be no capacity limit. The load transported by glacial ice on its surface is known to be large for the valley glaciers, but for continental glaciers it appears to be small, as the great ice sheets of Greenland and Antarctica seem to be mostly surfaced with pure ice. No quantitative estimates of the actual loads carried by glacial ice appear to have been made, but the total quantity is very great.

Causes and Places of Deposition. On melting, the ice either transfers its load to the melt waters or deposits it, the deposits being spread locally beneath the ice and generally around its margin. Deposition is thought to take place beneath the ice in those places where it becomes overloaded and it is easier to override a portion than to push it along. Direct deposition from ice at the ends of glaciers is responsible for the unstratified parts of moraines, and that beneath the glaciers for drumlins and the unstratified, unorganized material which in part constitutes the ground moraine. The burden transferred to melt waters is in part deposited over, and in association with, the unstratified deposits. As the waters issuing from glaciers commonly appear to have considerable velocity, it follows that the material deposited by them will have the characteristics of such deposition. The

overloading beneath the ice may arise from some obstruction encountered, giving rise to the crag and tail feature, wherein a mantle of till margins the lee side of the obstruction while the stoss side is more or less bare; or it may arise from an excess of material near the base of the ice. It was presumably under the latter conditions that the drumlins were formed, and hence the materials of drumlins should be generally lacking in marks of water deposition. The eskers, on the other hand, are ordinarily explained as arising from subglacial streams, but they have also been interpreted as accumulations of débris in crevasses either through material dropping in from above or through lateral shove.[197] The fact of washing and sorting in eskers would, however, seem to preclude this latter origin.

Deposition by glaciers may take place on the land, and in rivers, lakes, and the sea, and the deposits are not likely to be any better sorted or stratified when made in water than when made on land. The advance of a glacier into a body of water may plow deposits previously made and produce great disturbance of previously existing stratification.

Characteristics of Glacial Deposits. Ice produces no sorting of the material it transports. On the contrary, the longer the transportation the greater appears to be the mixing, both as to kinds of material and dimensions. The result is that deposits made directly by ice are mixtures of all sorts of material, with small and large angular fragments lying in the midst of finely divided material, of which some may be decomposed, but much is rock flour and somewhat larger fragments, the result of rock grinding and abrasion. This fine material is not apt to have been greatly leached at the time of deposition, and hence may have a high soda-potash ratio and be high in substances which are readily leached away.[198] It should be kept in mind, however, that there are fine materials of other origins which exhibit the same characteristics. As water is always present at the ends of glaciers, it results that stratified bodies of sediments occur in connection with those which are unstratified. The proportion of the two varies from point to point, and cross sections of a glacial deposit show stratified and unstratified materials dovetailing into each other.

The changes which take place in glacial transportation are physical; there is essentially no decomposition. This permits the tracing of the material of ice deposits to original sources. The larger pieces deposited directly from glacial ice are generally angular and subangular and may be soled and marked with striæ, although subsequent water transportation may round the angles and obliterate the striæ. Von Engeln expressed the opinion

[197] Millis, J., What was the cause of eskers? Science, vol. 39, 1914, pp. 208–209.

[198] Walker, T. L., A chemical study of conglomerates, Univ. of Toronto Studies, Geol. Series, vol. 12, 1921, pp. 63–67.

that the type glacial pebbles have a flat-iron shape.[199] The writer, however, hesitates to accept this view, preferring to refer the shapes of the smaller rock particles found in glacial deposits very largely to inheritance resulting from method of breaking from the parent rock. Chatter and percussion marks are developed, but they do not appear to be different from those due to other methods of transportation. The rock flour and somewhat larger particles are usually little rounded, as these particles have been ground or crushed from other rocks, but the rounding depends on the sources of the particles. If they were derived from sandstones of a previous cycle of deposition, the characters then given will be retained. The range in mineral composition of these small particles is commonly very large.

Striations and grooves may also be developed on pebbles and rock fragments which have been involved in crustal movements or have participated in rock slides. A study of the field relations in most instances should serve to differentiate the striations due to glacial transportation from those developed in other ways, but it may not always do so. Recourse must then be had to the abundance of the striated rock fragments, and the character of the striæ themselves. While striated pebbles are not so abundant in glacial deposits[200] as they ordinarily are supposed to be, they are more abundant in such deposits than elsewhere.

Glacial and earth-slide scratches are developed under pressures which do not often exceed the crushing strengths of the rocks involved, so that rock flowage is not likely to occur, whereas in earth movements the rocks are under pressures which may be sufficiently great to produce rock flow,[201] and the presence of the latter margining striations and grooves is strong evidence against these being of glacial origin. The object producing the scratch or groove might also be found in the latter case, but there would be little change in the former. The striæ made on loose material borne in the ice as a rule are in several systems and on the several sides of the rock fragments, as these are turned several times during transportation, whereas rock fragments involved in crustal movement and landslides are not likely to have striations in more than one system or on more than one side.

Considered as a whole, deposits made by glacial ice resemble landslide deposits in so far as stratification, angularity of particles, and variety of constituents are concerned; but the latter have a smaller variety of constituents, fewer striated and soled pebbles, and no contemporaneous

[199] Von Engeln, O. D., Type form of facetted and striated glacial pebbles, Am. Jour. Sci., vol. 19, 1930, pp. 9–16.

[200] Gregory, H. E., Notes on the shapes of pebbles, Am. Jour. Sci., vol. 39, 1915, p. 303.

[201] Woodworth, J. B., Boulder beds of the Caney shales at Talihina, Oklahoma, Bull. Geol. Soc. Am., vol. 23, 1912, pp. 457–462.

stratification. There is also likely to be a greater abundance of very large fragments in landslide deposits, and the fine materials show far more decomposition.

Soled pebbles may be simulated to some extent by the facets developed in wind work, the so-called dreikanter, but the facets of the latter are generally, if not always, pitted. Facets are also developed under certain conditions on stream pebbles, but field relations and the character of the associated materials should permit ready differentiation.

Glacial deposits to some extent are simulated by those of torrential streams and mud flows, as the latter may contain large, poorly rounded rock fragments and very poorly sorted and stratified portions interlensed with others that are better stratified, thus giving a cross section which may resemble that of a moraine. Igneous conglomerates may also resemble a deposit of glacial origin.[202]

Although the surfaces over which ice has moved are not deposits, they may be a part of the evidence by which the glacial origin of certain sediments is determined. These surfaces are polished, grooved, and striated, but the same effect to some extent may be simulated along fault planes and on surfaces over which rock slides have occurred. Wave-eroded sea bottoms may also be striated by rock particles held in shore ice. A careful study of the field relations should readily determine the origin of such surfaces.

Physiographic Forms Resulting from Glacial and Aqueo-glacial Deposition, and the Sediments Which Compose Them. Forms resulting from direct deposition by glacial ice are drumlins and moraines. Kames, eskers, and outwash plains result from melt-water deposition. The drumlins contain little or no stratified material, whereas frontal moraines[203] are composed chiefly of unstratified till, but also contain considerable bodies of stratified material. The ground moraine is an interlensing of both stratified and unstratified till which forms a cover of variable thickness over the surface of glacial retreat.

Eskers are composed mainly of washed sands and gravels and are commonly interpreted as the deposits of subglacial streams, but it has been suggested that they may be due to the backward extension of kames of a retreating glacier.[204] As the materials are stream-deposited, they were once sorted and stratified; but as the depositing waters probably had considerable velocity and these sediments were underlain by more or less ice at the time

[202] Gregory, H. E., The igneous origin of the "glacial deposits" on the Navaho Reservation, Arizona and Utah, Am. Jour. Sci., vol. 40, 1915, pp. 97–115.

[203] Moraines as here used applies to material which has been deposited, and not to drift in transportation.

[204] Trowbridge, A. C., The formation of eskers, Proc. Iowa Acad. Sci., vol. 21, 1914, pp. 211–218; Abstract, Science, vol. 40, 1914, p. 145.

of deposition, neither sorting nor stratification may be apparent. The kames which flank the stoss sides of moraines, or the delta-kames made where glaciers terminate in standing water, are deposited by torrential waters and consist of interbedded sands and gravels, although some silt may be present. Melt waters spilling over moraines drop their sediments on the lee side, the fineness increasing with distance from the ice front, so that the outwash plains are underlain by deposits ranging from gravels and sands near the moraines to the finest of rock flour at considerable distances away. A section from a ground moraine through a frontal moraine to the outwash clays would show an interlensing of stratified and unstratified material in the ground moraine, more or less rudely stratified material on the stoss side of the frontal moraine, mostly unstratified material in the moraine, and stratified material through the outwash with here and there a large boulder, the deposit from an ice block floating in the melt waters which were responsible for the outwash.

Transportation and Deposition by Sea, Lake, and River Ice

In polar latitudes some portions of the sea remain frozen during a part or the whole of the year, and in shallow waters freezing extends to the bottom. Upon the surface of such ice, particularly the shoreward portions, rock particles are blown by the strong winds which are known to be rather characteristic of parts of the polar world,[205] and are dumped by streams which begin to flow on the land before the ice leaves the shores. Some of the material freezes to the bottom, and by deformation and overturning of the ice may be brought into its interior and even to its surface. The results are that in many places polar ice carries a large content of sediment, and as salt-water ice has great resistance to buffeting by the waves,[206] these sediments may be transported for long distances.

Winds and waves may shove this ice on shore, to and upon which it may transport and deposit sediments,[207] or various sheets of the ice may "telescope" or "underrun" to produce ice floes of great thickness, and these, forced against each other by waves and winds, may be thrown into "ridges thirty feet high or more" or "tumbled about like corks in the water."[208] Where floes touch bottom, the latter is plowed to greater or less extents and must undergo considerable disturbance, and in this way some sediments are likely to be picked up and incorporated in the ice. It is known that

[205] Peary, R. E., Northward over the Great Ice, vol. 2, 1891, p. 238.

[206] Kindle, E. M., Observations on ice-borne sediments by the Canadian and other Arctic expeditions, Am. Jour. Sci., vol. 7, 1924, pp. 251–286. This article has been extensively used in the preparation of this topic.

[207] Stefansson, V., My life with the Eskimo, 1913, p. 384.

[208] Stefansson, V., The friendly Arctic, 1922, pp. 145–146.

floes occasionally ground in fairly deep water, one instance recorded relating to a "very large, long, hummocky floe, at least ten miles in length, several miles in breadth, and aground in 80 feet of water"[209] off Cross Island on the coast of Alaska. A survey of the bottom near Point Barrow on the northern coast of Alaska by Stockton "demonstrated that the contour of the bottom is constantly changed by the ploughing and planing done by the heavy ice grounded and driven up by the pressure of the mighty ice pack, under the influence of northerly winds and gales."[210] That similar work was done during past geologic periods appears very probable, but little of it has been found, or else it has been referred to other causes.

Icebergs are partly of glacial and partly of floe-ice origin, but whatever their source they contain much débris, Kane stating that "Of nearly five thousand bergs which I have seen, there was, perhaps, not one that did not contain some fragmentary rock."[211] The material so transported receives wide distribution. At the present time little of that derived from the Arctic region enters the Pacific, but the North Atlantic must be receiving a great deal, and it is being deposited in all sorts of marine environments.

As the ice of the polar seas is inhabited by considerable life—seals, bears, foxes, etc.—and the bottom has a considerable population, there is little doubt that from time to time remains of these are incorporated in the ice and carried to the places of melting. Surface organisms may enter the ice from the top. Marine benthos may be scooped up as the ice ploughs the bottom sediments or may become frozen in the ice at the bottom. Debenham[212] explains how this bottom material may ultimately rise to higher positions in the ice and even to its surface. In South Victoria Land, Antarctica, he found marine muds, shells, sponges, cœlenterates, fish, and the mineral mirabilite in the ice and on its surface at levels ranging from 5 to 35 feet above sea level, and in one occurrence 200 feet above sea level. The organisms within the ice in many cases were in the positions of growth, and organic remains were found 15 miles from the edge of land ice. The mirabilite in places was at least a foot thick. The explanation was offered that the water freezes at the bottom of the ice, thus incorporating the organic matter. At the same time, the freezing concentrates the salts in solution in the remaining water to such an extent that where circulation is poor, mirabilite is precipitated and ultimately frozen in the ice. As there

[209] Stockton, C. H., Arctic cruise of the U. S. S. "Thetis," Nat. Geog. Mag., vol. 2, 1890, p. 185.

[210] Stockton, C. H., op. cit., p. 182.

[211] Kane, E. K., The U. S. Grinnell Expedition in search of Sir John Franklin, 1854, p. 457.

[212] Debenham, F., A new mode of transportation by ice, etc., Quart. Jour. Geol. Soc., vol. 75, 1919, pp. 51–76.

is more or less continued dissipation of ice on the surface, the result is that the entire body of the floating ice is rising, thus raising materials derived from the bottom and ultimately bringing them to the surface. Debenham suggests that the physiography of certain coast shores and bottoms favors the occurrence of the phenomena described, and that the northern coast of North America presents most favorable possibilities. Remains incorporated in ice in this and other ways seem to be large in amount, and Stefansson's statement of "bushels of small shells" in the ice pressure ridges showed how portions of a polar fauna may be carried into temperate and perhaps tropical waters.[213] Such occurrences present splendid opportunities for paleontologists to go wrong.

Lake ice effects results similar to those of sea ice, but of less intensity, and the débris attains far less extensive distribution. Ice-borne material may thus be distributed over the entire bottom of a lake, making it possible for large fragments to be deposited with the finest of lake sediments.[214]

Similar transportation is accomplished by streams. North-flowing rivers are likely to give greater results than those which flow south, since in the former melting begins at the sources, and melt waters flow over ice at the mouth and may discharge upon ice at the sea. As previously noted, this is one way by which shore ice acquires sedimentary materials.

TRANSPORTATION THROUGH ACTION OF GRAVITY AND CHANGES OF TEMPERATURE

Transportation of sediments through the action of gravity and changes of temperature is well-nigh universal over the entire surface of the land. Its effects are greatest on steep slopes and gradually decrease to nothing on level surfaces. Changes of temperature tend to move material down the slopes. If material expands, the expansion is in the direction of least resistance, generally downhill. If the water in surface materials freezes, the expansion also tends to be in a downhill direction. If contraction takes place, the movement is more likely to be down than up. The movement brought about by one expansion or one contraction is small, but the process is often repeated and time is long. Davidson determined the rate of movement in summer, slope not stated and average daily range of temperature 14.4°F., to equal 0.00171 inches per day, and in winter, average daily range of temperature 8°F., to equal 0.00121 inches. This gives a movement of nearly a foot in 5 years.[215]

[213] Stefansson, V., The friendly Arctic, 1922, p. 515.

[214] Von Engeln, O. D., Transportation of débris by icebergs, Jour. Geol., vol. 26, 1918, pp. 74–81.

[215] Davidson, C., Second note on the movement of scree material, Abstracts, Proc. Geol. Soc. London, no. 525, 1888, p. 122.

As a consequence of the above forces, no sooner are sediments or soils produced than they begin to creep[216] to lower levels. As a rule, movement is extremely slow; it can rarely be seen except in accomplishment; but it affects every particle resting on slopes. If slopes are steep, the movement may be a rock fall or slide, with thousands of tons of material involved. Seismic disturbances often initiate rapid movement, as illustrated by the slides in loess deposits accompanying the Chinese earthquake of 1920.[217]

If the surface materials are saturated with water, movement may also

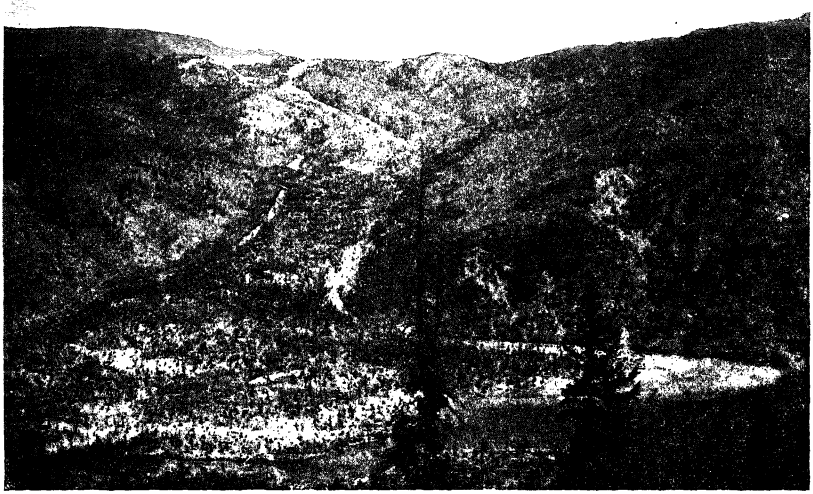

FIG. 6. SLUMGULLION MUD FLOW, SAN CRISTOBAL QUADRANGLE, COLORADO
Shows flow from source to termination. Photograph by United States Geological Survey.

become rapid, reaching its culmination in that type of earth movement known as mud flow, wherein earth with water flows as a stiff, viscous liquid. The quantity moved in some instances is very great, the Slumgullion mud flow (fig. 6) on the Lake Fork of the Gunnison River being of such magni-

[216] Creep as here used is to be distinguished from "continental creep" as employed by Chamberlin and Salisbury, Geology, vol. 2, 1906, p. 131, in which there is assumed to be a gradual settling outward of the bases of the continental masses through molecular and other adjustments of the basal materials.

[217] Close, U., and McCormick, E., Where the mountains walked, Nat. Geog. Mag., vol. 41, 1922, p. 463.

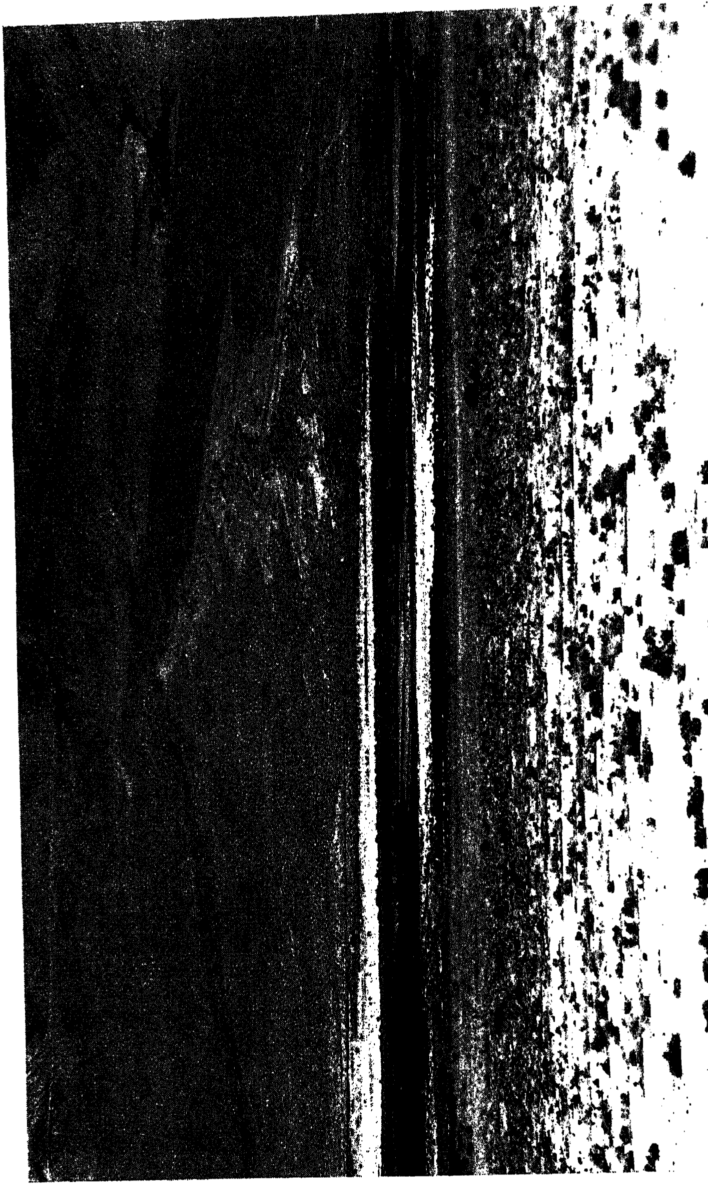

FIG. 7. A RECENT MUD FLOW ON A LARGE ALLUVIAL FAN

West base of White Mountain, northeast of Bishop, California. Telephoto view from a distance of 3 miles, made by Eliot Blackwelder.

tude that it led to the formation of Lake San Cristobal.[218] This flow started at an elevation of about 11,500 feet and traveled nearly 7 miles through a vertical distance of about 2600 feet on an average slope of nearly 5 degrees. The flow was not observed, but it is probable that the materials at the place of origin became so thoroughly soaked with water as to yield, and flowed as a river of mud and rocks down a lateral gulch to the Slumgullion River and thence to the Lake Fork and down that for about $\frac{3}{4}$ mile, a total distance of about $6\frac{3}{4}$ miles.[219] Mud-flow occurrence is favored by semi-arid climatic

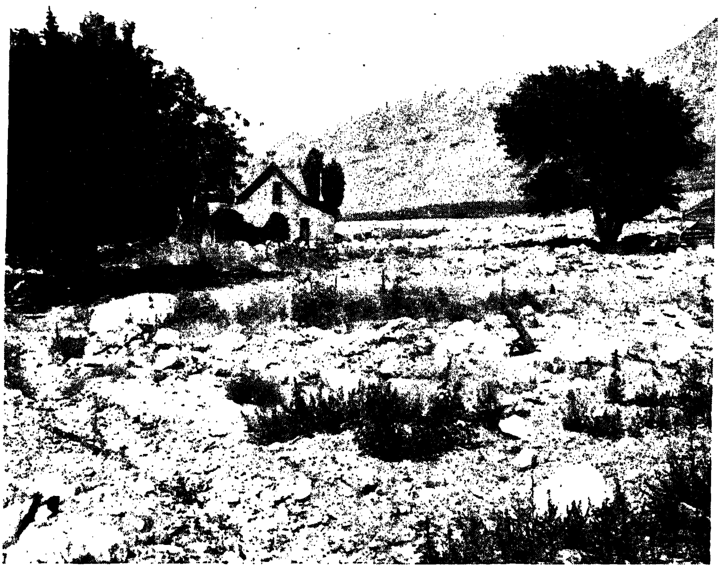

FIG. 8. A GARDEN IN THE VILLAGE OF WILLARD, UTAH, AFTER THE GREAT MUD FLOW OF 1924
Photograph by Eliot Blackwelder

conditions and surfaces of adequate relief. Considerable quantities of unconsolidated materials are also essential. Semi-aridity favors the fall of rain in occasional downpours and precludes the development of a vegetable cover of sufficient magnitude to protect and reinforce the surface materials. Volcanic ash seems to be excellent material for mud flows. Regions with consistent rainfall have much loose material removed, and the quantity

[218] Endlich, F. M., Rept. U. S. Geol. and Geog. Surv. Terr., for 1874, p. 203.

[219] Howe, E., Landslides in the San Juan Mountains, Prof. Paper 67, U. S. Geol. Surv., 1909, pp. 40–41.

left is usually not sufficiently great to produce mud flow. Mud flows of the western deserts described by Blackwelder ranged in thickness from 1 or 2 inches to several feet, most being 6 to 20 inches thick, the thicker flows being confined to the steeper alluvial fans (figs. 7–9). Some of these were 3 to 6 feet high at their edges. The liquidity of the flowing mud was found to vary greatly, and likewise there was great variation in the quantity of boulders and broken rock it contained. The more viscous mud contained the most boulders and did not move so far, coming to rest on the upper parts of the fans, whereas the "thin" mud contained few or no large boulders and

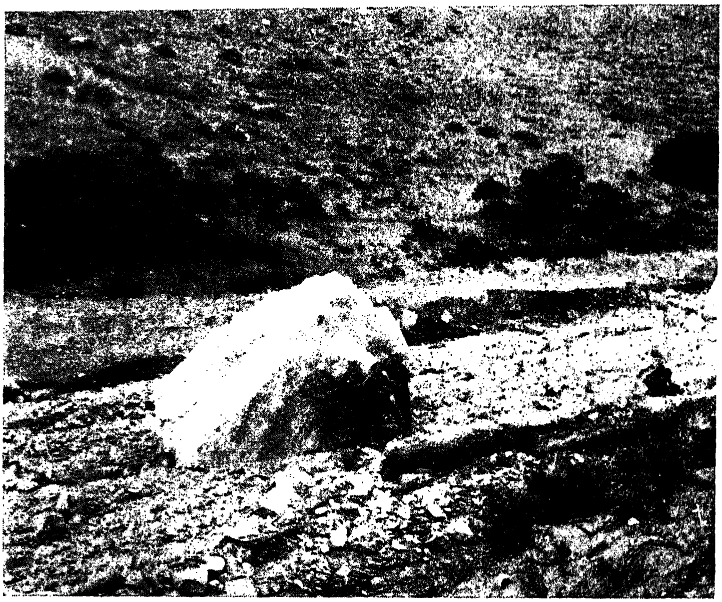

FIG. 9. A BLOCK OF QUARTZITE MOVED ABOUT ONE MILE DURING THE MUD FLOW AT WILLARD, UTAH, IN 1924
Photograph by Eliot Blackwelder

tended to flow beyond the edges of the fans in digitate or lobate fashion. Little water may be present,[220] Pack citing a flow in which the quantity was so small that not a trickle appeared at the margin. The more viscous muds carry the largest boulders, blocks 10 to 20 feet in diameter being common, and some blocks have been observed which were 40 to 50 feet long. A block with dimensions of 8 by 16 by 12 feet is known to have been carried a dis-

[220] Pack, F. J., The torrential potential of desert water, Pan.-Am. Geol., vol. 4, 1923, pp. 349–356.

tance of 7 miles. Blackwelder's[221] description of a flow at Willard, Utah, is as follows (figs. 7–8).

The churned-up mass of slimy earth, trees, and boulders gathered momentum as it descended the gorge and burst forth upon the plain at the village of Willard with sufficient impetus to carry it half way down the slope of the fan. It covered the former surface with a layer of bouldery mud 3 to 4 feet deep. The flow deployed rapidly through the village, surrounded houses, carried off small outbuildings or crushed them like eggshells and overspread the concrete roadway for hundreds of feet. . . . The front of the flow was about 3 feet high and almost as steep as the edge of a lava coulee. The most striking characteristic of the flow is the abundance of boulders which range in diameter from 1 to 15 feet. . . . The whole mass is as unstratified as glacial till.

Mud flows of various degrees of magnitude also occur in regions subject to frequent freezing and thawing and with limited fall of snow. The soil usually thaws to a shallow depth at the top while remaining frozen below, the thawed soil then behaving as a viscous liquid. One of the best descriptions of this phenomenon is that of Belcher with respect to the conditions on Buckingham Island.[222] Describing soil which had been frozen in the morning, he states:

As noon passed the soil in all the hollows or small water courses became semifluid and very uncomfortable to walk on or sink into. At the edge of the southern bank the mud could be seen actually flowing, reminding one more of an asphalt bank in a tropical region than our position in 70°10′ N. The entire slope in consequence of the thaw, had become a fluid moving chute of débris at least a foot in depth.

In the Alps Dickson[223] has described "a stream of mud slowly descending the mountain side, carrying on it and in it stones and boulders." Thawing had converted the soil into a slimy mud, which, descending "with resistless force," carried "destruction far and wide." He states, "There are records to show, that one of these avalanches many centuries ago descended the same mountains" (Dent du Midi) "and utterly wiped out one of the towns in the valley." From Patagonia Coppinger[224] has described occurrences in which the soils and supported vegetation were slowly sliding downward over surfaces previously smoothed by ice erosion.

Movement due to thawing evidently is limited to a relatively thin surface zone whose thickness depends on the texture, color, permeability, relief, plant covering, and possibly other characters of the surface materials.[225]

[221] Blackwelder, E., Mud flow as a geologic agent in semi-arid mountains, Bull. Geol. Soc. Am., vol. 39, 1928, pp. 465–483 (469).

[222] Belcher, Sir Edward, The last of the Arctic voyages, vol. 1, p. 306.

[223] Dickson, E., Mud avalanches, Proc. Liverpool Geol. Soc., vol. 6, pt. iv, 1892, pp. 387–395. See also Conway, W. H., Geog. Jour., vol. 2, 1893, pp. 291–293.

[224] Coppinger, R. W., On soil-cap motion, Quart. Jour. Geol. Soc., vol. 37, 1881, pp. 348–350.

[225] Eakin, H. M., Bull. 631, U. S. Geol. Surv., 1916, p. 76.

Andersson designated this manner of movement of materials *solifluction* and it seems very probable that it is important in high latitudes[226] and altitudes. To solifluction Andersson refers the "stone rivers" of the Falkland Islands, described by Darwin[227] and Thomson.[228] According to the latter, these are composed of blocks of quartzite up to 20 feet long and 10 feet wide, distributed in stream-like outlines "from a few hundred yards to a mile or two in width," and "look at a distance much like glaciers descending" from the nearby ridges. These masses are not now in motion, and they were thought by Thomson to have moved through expansion and contraction.

On Bear Island in the Arctic Ocean are many "rock streams," and the surface is almost barren of vegetation except in the crevices of the rocks. According to Dr. Swenander, an associate of Dr. Andersson in the study of Bear Island, the barrenness of the surface is due to the fact that the plants cannot adapt themselves to the moving soil. One of the "streams" on the top of Oswald Hill on Bear Island had a breadth of 35 meters and a thickness of at least 2.1 meters. At the anterior edge of this "stream" was a "zone of sandstone plates, pushed together so that they were standing edgewise beautifully concentric to the rounded front of the detritus tongue," the piled-up zone having a width of 17 meters.

The flows of volcanic ash are frequently of great extent. One described by Scrivenor[229] flowed for 38.25 kilometers, and the breadth of country traversed by the flows was 20.25 kilometers. Individual flows were 4 kilometers wide, and a total area of 131.2 square kilometers was covered with mud-stream deposits. In the village of Blitar the streams were 1.5 to 2.5 meters high. Boulders and smaller stones were transported long distances, one boulder being 10 feet high and wide and more than 10 feet long. Some boulders were scratched, and one had both a scratched and polished surface.

Still another variety of mud flow is that known as bog burst, in which bogs lying on surfaces of low relief overspread their confining barriers at some point and invade lower lands as streams of peat.[230] Barkley describes a bog burst occurring on the Falkland Islands in which a stream of half-liquid peat, over 100 yards wide and 4 to 5 feet deep, flowed through the town of Stanley to the harbor, blocking streets, wrecking a couple of houses, and smothering a child and perhaps an old man.

[226] Andersson, J. G., Solifluction, a component of subaerial denudation, Jour. Geol., vol. 14, 1906, pp. 91–112.

[227] Darwin, C., Voyage of the Beagle, 1841.

[228] Thomson, W., The Atlantic, p. 245.

[229] Scrivenor, J. B., The mudstreams ("Lahars") of Gunong Keloet in Java, Geol. Mag., vol. 66, 1929, pp. 433–434.

[230] Barkley, A., Description of a bog burst back of the town of Stanley, Falkland Islands, Abstracts, Proc. Geol. Soc. London, 1887, p. 9.

A somewhat different expression of the movement of materials is that exhibited by the Gros Ventre earth flow of 1908 to 1911. This took place on the Lake Creek tributary of the Gros Ventre River in the mountains south of Yellowstone Park, the materials involved consisting of soft shales and clays with some sandstone and limestone.

> When first observed the disturbance was manifested only at the head of the gulch, where large masses of the slippery Morrison and Sundance (Jurassic) clays had slumped down along the steeper slopes, overturning trees and leaving a general wreck. Either quickly or slowly, the impulse from this upper mass was then communicated to the old landslide débris farther down the valley, and that in turn began to press forward, bulge, and crack. The novel thing about this case is that the movement of at least the lower part was very slow and yet continuous, like that of a glacier.[231]

The movement was so slow that it could not be observed, but it appears to have been continuous, as the roads across the slide could not be maintained, and the Forest Service telephone line which passed over the slide could not be kept in repair. The movement appeared to have been greatest during the wet months. Near the lower end of the flow very characteristic crevassed bulging domes were developed.

A gentle movement of material may also occur in which large rock masses are involved, which slowly slide down slopes in the manner of a glacier. These are known as rock slides (following Howe's classification), and it has been stated by him[232] that in movements of this kind, in which large blocks are involved, "the blocks tend to rotate backward about axes parallel to the strike of the slope down which they are descending." This rotation to some degree may be observed on any slope on which large blocks are slowly sliding downward after having broken away from strata farther up the slope. The attitudes depend to a large extent on the original ones, but if the strata from which the blocks were derived were essentially horizontal, it will be found that large numbers have the original upper surface inclined into the slope. The quantity of material moved by rock slides in some regions is extremely great, and in some highlands it is among the most important methods of transportation of material.

In rock falls movement is rapid, the material falling with sufficient force to become considerably shattered. Howe[233] described the rock fall and slide at Frank on the slope of Turtle Mountain as "a succession of great leaps or richochets, probably accompanied by a certain amount of rolling and sliding," and long before the rocks came to rest they had been shattered to fragments by impacts against the side of the mountain. In such rapid

[231] Blackwelder, E., The Gros Ventre slide, an active earth-flow, Bull. Geol. Soc. Am., vol. 23, 1912, pp. 487–492.

[232] Howe, E., op. cit., pp. 53, 55.

[233] Howe, E., op. cit., p. 53.

movements a rotary movement is developed which, in contrast to that in rock slides, is forward, or at least it becomes forward at the first impact with any object, and when the falling mass finally lands, the shattered rock composing it moves outward in its upper parts and extends lobes of material beyond the main body of the fall. This is Howe's explanation of the origin of "rock streams."[234] His description of a "rock stream" is as follows:

> In general appearance these accumulations resemble long tongues or lobes of talus stretching far out from the base of the cliffs from which they were derived over the nearly level surface or gently sloping floors of the cirques. The deposits are usually bounded by a sharply defined steep front or outward face or embankment. Their surfaces are seldom smooth, but are marked by irregular hummocks separated from one another by deep, narrow depressions, or by concentric ridges that lie one within another from the end of the stream inward. The material of the rock streams consists of angular blocks of rock, variable in size, but usually averaging about a foot in diameter. Masses 15 feet or more in diameter are not uncommon, while an abundance of fine angular gravel or coarse sand is noticeable near the outer margins of these rock streams, especially at the foot of the steep embankment.[235] (See figs. 10–11.)

Features somewhat similar to "rock streams" are the "rock glaciers" described by Capps[236] from the Nizina Quadrangle, Alaska. These lie in cirques, are composed of angular talus, range in area from a width of $\frac{1}{10}$ to $\frac{1}{4}$ mile and from $\frac{1}{2}$ to $2\frac{1}{2}$ miles long. In some cases they have broad fan-shaped heads and terminate in narrow tongues; in others the heads are pointed and the terminations fan-shaped. The composing rock fragments are usually small, but in exceptional cases they attain diameters of several feet. The surfaces of the "rock glaciers" in the upper portions commonly have many parallel longitudinal ridges, where the lower ends are characterized by concentric wrinkles parallel to the front. Just a few feet beneath the surface the interstices between the rock fragments are filled with ice. It was suggested that the freezing and thawing of this ice was responsible for the formation of the "rock glaciers."

Subaqueous landslides are probably of common occurrence. (See p. 742.) Yamasaki states that after the great Japanese earthquake of 1923 there were submarine fault scarps along which submarine slides occurred, and at one place there was a "great slip 10 kilometers long, similar to a mountain

[234] Another explanation of these phenomena has been advanced by Cross, Silverton Folio, No. 120, U. S. Geol. Surv., 1905. Cross considers that they are "rather unusual types of moraine" which are developed "as a result of landslides on the surfaces of small glaciers which lingered on in the cirque some time after the retreat of the ice of the main valleys."

[235] Howe, E., op. cit., p. 49.

[236] Capps, S. R., Jr., Rock glaciers in Alaska, Jour. Geol., vol. 18, 1910, pp. 359–375.

FIG. 10. HUMMOCKY SURFACE OF LANDSLIDE DEPOSIT, RED MOUNTAIN LANDSLIDE DISTRICT, SILVERTON QUADRANGLE, SOUTHWEST COLORADO
Photograph by United States Geological Survey

FIG. 11. ROCK STREAM AT HEAD OF SILVER BASIN, SILVERTON QUADRANGLE, SOUTHWEST COLORADO
Photograph by United States Geological Survey

slip on the land surface, filling the floor of the furrow with débris 230 meters in thickness."[237]

Great quantities of material are moved in some of the slides and falls. In the Frank slide of 1903 enough material was moved to cover the valley at the foot of Turtle Mountain over an area of 1.03 square miles to a maximum depth of 150 feet,[238] and a Himalaya landslide in September, 1893, moved material to the estimated quantity of eight hundred million tons.[239]

When rocks fall or slide in the manners described, certain important characters are developed. There is no sorting of material. Large pieces lie in the midst of small, and there may be nests of extremely large blocks surrounded by much finer material, as described by Rich[240] near Silver City, New Mexico, where blocks of rhyolite of many tons' weight lie surrounded by alluvial fan gravels, into which Rich postulates they slid. The fragments transported by slides are probably larger than those carried in any way other than by ice, a block more than 2 miles long having been reported from Colorado[241] and one more than ½ mile long from Idaho.[242] The impact of rock on rock produces chattermarks. Fragments may be rubbed over the surface on which the slide occurs, or moved differentially with respect to each other in the mass of moving material, with the result that polished, soled, and striated fragments are developed, and similar markings may develop on the surface over which a slide moves. Fragments may also be rotated in the mass of moving material so as to become somewhat rounded. The deposits have hummocky surfaces somewhat similar to a glacial moraine, which internally they also resemble (figs. 6–7).

These methods of transportation bring material directly to the sites of deposition, but their greatest function seems to be feeding of streams, both water and ice. Quantitative estimates cannot be given, but the transportation must be ranked as high in volume.

Ancient Rock Slides

Examples of ancient rock slides have been identified from the geologic column in few instances. This may have arisen, not because of their absence, but because students have not had in mind the transportation and

[237] Yamasaki, N., Physiographical studies of the great earthquake of the Kwanto District, 1923, Jour. Faculty Sci., Imp. Univ. Tokyo, vol. 2, 1926, p. 99.

[238] McConnell, R. G., and Brock, R. W., Report on the great landslide at Frank, Alta., Canada, Ann. Rept. Dept. Interior, for 1902–1903, pt. viii, 1903.

[239] Davis, W. M., Physical geography, 1899, pp. 182–183.

[240] Rich, J. L., The occurrence of unusually large boulders in gravel deposits, Am. Jour. Sci., vol. 38, 1914, pp. 441–445.

[241] Cross, W., 21st Ann. Rept., U. S. Geol. Surv., pt. ii, 1900, p. 146.

[242] Russell, I. C., 20th Ann. Rept., U. S. Geol. Surv., pt. ii, 1899, p. 19.

deposition of material in this manner and have assigned deposits to other origins.

An example wherein this method of transportation is thought to have brought material to the sea is furnished by the Cow Head conglomerates in the Ordovician on the west coast of Newfoundland. These conglomerates have a thickness of about 700 feet and consist of large and small blocks of limestone and shale of Early Ordovician age imbedded in a limestone matrix of Middle Ordovician age. Some of the rock fragments are of enormous dimensions, one on the east side of Cow Head Peninsula having an estimated length of over $\frac{1}{8}$ mile. These blocks are thought to have slid into the sea from the top of the Middle Ordovician Long Range. A somewhat similar origin has been postulated by Bailey, Collet, and Field[243] for the famous conglomerates in the Ordovician strata beneath, adjacent to, and south of the city of Quebec. The same authors, following Schardt,[244] suggest that the "blocs exotiques" of the early Tertiary *wildflysch* of the Alps represent blocks which slid into the stratified deposits from "northwardly advancing thrust masses." A slide deposit connected with fault movement occurs in Cretaceous sediments at Brora on the east coast of Scotland,[245] and Grabau[246] has described a breccia of Silurian age near St. Ignace in the Upper Peninsula of Michigan which he refers to landslide origin. Lately it has been suggested that the boulders in the Caney shale of Oklahoma may be blocks that slipped from the hanging wall of one of the thrust faults of southeastern Oklahoma.[247]

TRANSPORTATION AND DEPOSITION BY ORGANISMS

Considerable quantities of sediments are transported by organisms, but it is extremely difficult to give quantitative data or make qualitative statements. Organisms are also important in placing material in an environment from which it may readily be transported by other agents.

Every plant as it grows displaces with its roots a considerable quantity of

[243] Bailey, E. B., Collet, L. W., and Field, R. M., Paleozoic submarine landslips near Quebec City, Jour. Geol., vol. 36, 1928, pp. 577–614.

[244] Schardt, H., Les régions exotiques du versant nord des Alpes suisses, Bull. Soc. vaudoise Sci. naturelles, vol. 34, 1898, p. 215.

[245] McGregor, M., A Jurassic shore-line, Trans. Geol. Soc. Glasgow, vol. 16, 1916, pp. 75–85; Lee, G. W., The geology of the country around Golspie, Sutherlandshire, sheet 103, Mem. Geol. Surv. Scotland, 1925, p. 107.

[246] Grabau, A. W., Subaerial erosion cliffs and talus in the Lower Devonic of Michigan, Sci., vol. 25, 1907, pp. 295–296; Principles of stratigraphy, 1913, pp. 546–547.

[247] Dixon, E. E. L., The Ouachita Basin of Oklahoma *vis-a-vis* the Craven lowlands of Yorkshire, Geol. Mag., vol. 68, 1931, pp. 337–344. See also Powers, S., Bull. Geol. Soc. Am., vol. 39, 1928, pp. 1031–1072 (1046), and van der Gracht, W. A. J. M. van W., Jour. Geol., vol. 39, 1931.

material. This displaced material is pushed out of the way in the direction of least resistance, generally downhill, as is excellently illustrated by trees growing near the edges of cliffs.

Every animal which digs a burrow in the ground carries the material more often downhill than up. Crayfish, muskrats, beavers, moles,[248] prairie dogs, gophers, skunks, ants,[249] and earthworms[250] bring millions of tons annually to the surface or dump it into streams, Darwin stating that under favorable conditions earthworms annually bring to the surface $\frac{1}{5}$ inch of earth.

Since his appearance, man has been a great agent of transportation, and there is little doubt that future generations of geologists will have little difficulty in tracing his paths of travel by the articles he has dropped along the way. In all lands he plows the material downhill, with the consequence that all plowed land over the hill portions of the world is moved downward from 6 inches to 1 foot for each plowing. The débris from his ships and the ships themselves occur in the sediments of all the seas, and it is certain that the material transported by man will be recognized in the sediments studied by geologists in the far distant future.

Indirectly, man has largely increased the sediments deposited by other methods. He has stripped the surface of vegetation over extensive areas, and in many regions has taken few precautions to retain the soils.[251] In other regions he has washed down hills in hydraulic mining, the volume thus moved in California alone totaling for 1849–1914 over a billion and a half cubic yards,[252] or nearly eight times as much as the material moved from the Panama Canal, itself a tremendous piece of animal transportation. Sherlock[253] expressed the view that "in a densely populated country, man is about five times as effective as a denuding agent as all natural agents combined."

On the bottoms of water bodies considerable transportation is effected by the animals which live there, but as the distance the material is carried is small, this matter is reserved for consideration in connection with other topics.

248 Shaler, N. S., Work of moles, rabbits and prairie dogs, 12th Ann. Rept., U. S. Geol. Surv., 1892, pp. 268–297.

249 Branner, J. C., The geologic work of ants, Bull. Geol. Soc. Am., vol. 7, 1896, pp. 295–300; Jour. Geol., vol. 8, 1900, pp. 151–153.

250 Darwin, C., Formation of vegetable mould, 1881.

251 Glenn, L. C., Denudation and erosion in the southern Appalachian region, etc., Prof. Paper 72, U. S. Geol. Surv., 1911.

252 Gilbert, G. K., Hydraulic-mining débris in the Sierra Nevada, Prof. Paper 105, U. S. Geol. Surv., 1917, p. 43.

253 Sherlock, R. L., The influence of man as an agent in geographical change, Geog. Jour., vol. 61, 1923, pp. 258–273 (259); Man as a geological agent, London, 1922. See also Fischer, E., Der Mensch als geologischer Factor, Zeits. d. deut. geol. Gesell., vol. 67, 1915, pp. 106–148.

Some transportation is brought about by floating trees. Uprooted trees not infrequently hold much material caught in their roots, of which in many instances large rocks constitute a considerable portion. This material may be floated long distances before the rocks are detached to drop into environments with which they are not in harmony. Thus, Andrews[254] has reported the occurrence of a quartzite boulder with dimensions of 12 by 18 inches half buried in the top of a coal bed at Zaleski, Ohio, and one[255] approximating 4 by 6 inches in the middle of a coal bed at Coal Creek, East Tennessee. Such have also been described from England[256] up to 8 inches in diameter. These boulders are not of quantitative significance, but they are important in interpretation.

In the sea there is some transportation of boulders by seaweeds, particularly the large laminaria which through their holdfasts firmly grasp the rocks over which they grow. Torn loose by waves or growing to such dimensions as to raise the rocks from their resting places, they may be drifted to deep or other waters, where the rocks entangled in their holdfasts are dropped and become incorporated in sediments of different character. The granite and other boulders up to 8 inches in diameter in the Carboniferous limestones of Dublin were probably thus transported.[257] Large-pored colonial corals are known to float for some distances in modern seas,[258] Guppy describing one with circumference of 7 feet. These may settle in waters of any depth in which they would not dissolve before reaching bottom, and on bottoms of any environment. It is probable that the *Favosites* type of coral of ancient seas had a similar ability to float.

Seals and penguins "carry to sea large numbers of stones and rounded pebbles in their stomachs, to which sailors give the name of 'ballast'."[259] These are dropped where the remains decay. Whether such was done by ancient marine organisms is not known, but the stomach stones (gastroliths) of the ancient dinosaurs were left in places where they did not originate.

As a whole, the transportation effected by organisms, man excepted, is not of great quantitative importance. It is, however, a factor which must

[254] Andrews, E. B., Rept. Prog., Geol. Surv. Ohio, 1870, p. 78.

[255] Bradley, F. H., Mentioned by Dana, J. D., Manual of geology, 1895, p. 664.

[256] Spencer, J., On boulders found in seams of coal, Quart. Jour. Geol. Soc., vol. 43, 1887, pp. 734–735; Bonney, T. G., On the occurrence of a quartzite boulder in a coal seam in South Staffordshire, Geol. Mag., vol. 10, 1873, pp. 289–291.

[257] Ball, V., On the probable mode of transport of the fragments of granite and other rocks which are found imbedded in the Carboniferous limestone of the neighborhood of Dublin, Quart. Jour. Geol. Soc., vol. 44, 1888, p. 371–374.

[258] Guppy, H. B., Scottish Geog. Mag., vol. 5, 1889, p. 287.

[259] Murray, J., and Renard, A. F., Deep sea deposits, 1891, p. 321. See references there cited.

be kept in mind in interpretation of deposits in whose formation organisms may have participated.

Deposition by organisms is responsible for large volumes of sedimentary rocks, many of the limestones, some of the siliceous and ferruginous sediments, and all of the carbonaceous sediments being more or less directly so deposited. As these sediments are discussed in detail under other headings, the problems connected with their deposition are omitted in this connection.

Interruptions of Deposition

Relative elevation of a surface so as to bring it above the water level is an important cause of interruption of deposition, and the one to which appeal is usually made to explain unconformities. However, deposition is interrupted in all deposits by causes which have nothing to do with elevation and which endure for periods of various extent. In every continental deposit, deposition comes to an end when a base level of deposition is reached, and does not begin again until there has been an increase in the supply of sediments, or a decrease in the competency and capacity of the transporting agents over the sites of deposition, the two factors being due to elevation of the sources of supply, depression of the sites of deposition, increased activity of the transporting agents at the supply, or decreased activity over the depositive area. It is generally assumed that submergence has deposition as its invariable accompaniment, but as noted by Andrée[260] this assumption has little or nothing on which to rest. Submergence may mean erosion.

Deposition in marine environments ends when the bottoms have been built to a profile of equilibrium. A bottom may be brought to this level by deposition or by relative uplift. Deposition then ceases until a new profile is determined by a rise of sea level, a sinking of the bottom, or some condition in adjacent regions increasing the volume of the sediments. Interruptions will also occur when sediments fail to be supplied.

Much of the existing sea bottom surrounding the continents appears to be below the profile of equilibrium; thus, deposition is taking place and the bottom is rising. Interruptions of deposition no doubt occur, but they are short. There are places where the profile of equilibrium has been reached and the bottom is receiving no deposits or is being eroded. About the mouth of the Choptank River in Chesapeake Bay, for example, the area which has received no deposits in the fifty-two-year period between 1848 and 1900 is four times that which has received deposits, and the area wherein deposition has been interrupted is at least four times that in which there is a

[260] Andrée, K., Geologie des Meeresbodens, Bd. 2, 1920, p. 312.

possibility that it may have been continuous.[261] The greater portion of this bottom appears to be at about the depth of the profile of equilibrium.

A few places are known in the open ocean where the bottom is receiving no deposits or is being eroded, and some of these occur in great depths. According to Agassiz, the surface of the Blake Plateau beneath the Gulf Stream is receiving no deposits and is "nearly barren of animal life."[262] In the Indian Archipelago, "hard bottom" exists between some of the islands to depths of 1500 meters, indicating that the bottom is not only receiving no deposits but is being eroded.[263] "Hard bottom" is known to obtain on the bottom of the passage between Gran Canaria and Teneriffe of the Canary Islands to a depth of 2000 meters,[264] and the bottom of the Strait of Gibraltar is clean and smooth.[265] On the submerged ridge (George's Bank) separating the deep inner portions of the Gulf of Maine from the Atlantic Ocean the deposits are so thin that late Tertiary strata are exposed, and a similar condition seems to obtain on the Grand Bank.[266] The depths on George's Bank range from 35 to 70 fathoms or more, and they are around 35 fathoms on Grand Bank. Rock-bottom areas are known about the British Isles to depths of 500 fathoms,[267] and many rock-bottom areas are known to be present in the shoreward waters of the Gulf of St. Lawrence.

Many interruptions of deposition are known in the geologic column. These have rather generally been explained as being due to uplift of the bottom followed by subaerial erosion; and in few instances have they been referred to non-deposition through the bottom having been built to the profile of equilibrium or having been raised above it. Willis has emphasized this possibility; stratigraphers have given it little favor.[268] Grabau has suggested that non-deposition obtained over a submerged surface near Kingston, New York, where a submarine ridge of folded and eroded Middle Ordovician sandstones may have projected above the bottom of the Middle Silurian sea so that Silurian deposits were formed around but not over it.[269] Cretaceous strata near Dresden have had the absence of certain beds ex-

[261] Hunter, J. F., Erosion and sedimentation in Chesapeake Bay around the mouth of the Choptank River, Prof. Paper 90, U. S. Geol. Surv., 1914, pp. 13–14.

[262] Agassiz, A., Three cruises of the 'Blake,' vol. 1, 1888, p. 259.

[263] Weber, M., Die niederlandische "Siboga" Expedition zur Untersuchung der marinen Fauna und Flora des Indischen Archipels, Petermann's Mitth., vol. 46, 1900, p. 187.

[264] Reade, T. M., Tidal action as an agent of geological change, Philos. Mag., vol. 25, 1888, pp. 338–343.

[265] Grabau, A. W., Principles of stratigraphy, 1913, p. 244.

[266] Verrill, A. E., Occurrence of fossiliferous Tertiary on the Grand Bank and George's Bank, Am. Jour. Sci., vol. 16, 1878, pp. 323–324.

[267] Lebour, G. A., On the deposits now forming in British seas, Geol. Mag., vol. 11, 1874, pp. 476–477.

[268] Willis, B., Principles of paleogeography, Science, vol. 33, 1910, pp. 246–251.

[269] Grabau, A. W., Principles of stratigraphy, 1913, p. 683.

plained as due to non-deposition.[270] Numerous breaks in the Jurassic limestones of the Alps have also been referred to cessations of deposition without the emergence of the surface above the level of the water.[271]

These breaks of supposedly minor duration have been designated diastems.[272] It is suspected that many of them are very long—as long as the time represented by many unconformities. Their recognition implies that the organic as well as the inorganic record is broken, and their presence should be suspected in those rocks in which organic remains are scanty or rather thoroughly comminuted.[273] They deserve extremely serious consideration.

Diagenesis and Lithification of Sediments

The consolidation or lithification of sediments may take place shortly after deposition, or be postponed to a distant future. It is not dependent upon age, although, as a rule, the older sediments are most lithified, but exceptions are many. Thus, Cambrian sands of Wisconsin are so little indurated that they may be removed with a shovel, and such is also true for sands and clays in the Cambrian of the East Baltic, whereas some recent shell deposits of Florida are sufficiently lithified to serve as building stones.

Between deposition and lithification a great variety of changes in sediments may occur. These changes are included under the term of *diagenesis*, which as here used is intended to embrace all modifications of sediments which occur between deposition and lithification under conditions normal to sedimentary environments, and all alterations after consolidation under normal conditions of temperature and pressure, but excludes those katamorphic changes having for their objective the disaggregation of the sedimentary materials. The latter qualification ordinarily implies that the sedimentary materials have not been uplifted and brought within the range of ground-water circulation.[274]

[270] Petrascheck, W., Studien über Facienbildung im Gebiete der sächsischen Kreideformation, Leipziger Inaugural-Dissertation, 1894, p. 26 et seq.

[271] Andrée, K., Über stetige und unterbrochene Meeressedimentation, ihre Ursachen, sowie über Bedeutung für die Stratigraphie, Neues Jahrb. etc., Beil. Bd., 25, 1908, pp. 366–421.

[272] Barrell, J., Bull. Geol. Soc. Am., vol. 28, 1917, p. 794.

[273] Wepfer, E., Ein wichtiger Grund für die Lückenhaftigkeit paläontologischen Ueberlieferung, Centralbl. f. Min., etc., 1916, pp. 105–113; Terrestrische Einflüsse bei der marinen Sedimentation und ihre Bedeutung, Zeits. d. d. geol. Gesell. Monatsb., Bd. 74, Nr. 1, 1922, pp. 39–47.

[274] Walther, J., Einleitung in die Geologie als historische Wissenschaft, 1893–1894, pp. 693–712; Andrée, K., Die Diagenese der Sedimente, ihre Beziehungen zur Sedimentbildung und Sedimentpetrographie, Geol. Rundsch., Bd. 2, 1911, pp. 61–74, 117–130. Andrée's definition is slightly different (p. 73), and he departs considerably from earlier definitions. See also his papers, Die paläogeographische Bedeutung sediment-petro-

Following deposition, sediments ordinarily are saturated with water more or less highly charged with dissolved and colloidal matter. It is probable that in some cases these waters subtract something from the surrounding sediments; in others they deposit some of their dissolved solids; and in still other instances interchange of material occurs between the waters and the sediments. As there may be slow movement of the contained waters, it follows that material may be introduced into sediments from above, from below, or laterally. The possible occurrences no doubt depend on temperature, pressure, material in solution, materials of the sediments, micro- and other organisms in the sediments, and other factors. Among the results are the change of aragonite to calcite; the formation of glauconite, the partial replacement or removal of calcium carbonate to form dolomite; the aggregation of silica to form flint and chert; the formation of concretions; the aggregation of iron sulphides and iron carbonate to form nodules and other forms of pyrite, marcasite, and siderite; and the change of calcium carbonate to calcium sulphate. It seems probable that there is much redistribution of materials in some sedimentary bodies before consolidation. Data are limited and the field of diagenesis is almost unexplored. The term has been much used, but there is very little exact information. Bottom deposits have been superficially studied near and at the surface; and a few facts relating to diagenesis have been learned; almost nothing is known of what takes place beneath the surface.

Many sediments contain considerable quantities of living and dead organic matter. Living organisms use both living and dead for food, and some also eat the containing sediments. Oysters and other mollusks, echinoderms, worms, and various other organisms eat vast quantities of the bottom. These materials pass through the intestinal tracts and are acted upon by the intestinal juices, but the changes which occur are little known. According to Jensen,[275] the evidence suggests that passage through the intestines of some organisms is attended by increase in nitrogen content. Some bacteria form ammonia; others form hydrogen sulphide, sulphur,[276] and sulphates; and carbon dioxide is formed by all animals and plants and results from the decomposition of all organic matter. The various conse-

graphischer Studien, Petermann's Mitth., vol. 59, 1913, pp. 117–123, 186–190, 245–247, and, Das Meer und seine geologische Tätigkeit, in Salomon, Grundzüge der Geologie, Bd. 1, 1924, pp. 435–436; see also Schuchert, C., Diagenesis in sedimentation, Bull. Geol. Soc. Am., vol. 31, 1920, pp. 425–432.

[275] Jensen, P. B., Studies concerning the organic matter of the sea bottom, Rept. 22 of the Danish Biol. Sta. to the Board of Agriculture, 1914, pp. 22–24.

[276] Trask, P. D., and Wu, C. C., Free sulphur in recent sediments, Abstract, Bull. Geol. Soc. Am., vol. 41, 1930, pp. 99–100.

quences of the work of organisms will receive extensive consideration in the chapter on the interrelations of sediments and organisms.

The different substances formed by organisms react with the containing sediments, resulting in the formation of sulphides, carbonates, sulphates, silicates, and other substances. Decaying organic matter acquires oxygen where available, and if free oxygen is not present, oxygen will be taken from substances yielding it. A common source of oxygen is ferric oxide, which, losing a part of its oxygen, is reduced to the ferrous form, in which condition it readily unites with carbon dioxide or hydrogen sulphide to form iron carbonate or iron sulphide. The sulphates constitute another source. These transformations change the colors of the sediments, and if the resulting products are removed by the contained waters, the chemical characters of the sediments are thereby modified. Thus, red clays and sandstones may be bleached to white,[277] or become black from contained iron sulphide.

Probable diagenetic changes occurring in the deposits of Lake Mendota near Madison, Wisconsin, are shown by the variations in the character of the materials at the top, middle, and bottom of 10-foot cores taken in depths of water between 60 and 80 feet. At the top the deposits are more than saturated with water, being a soup-like mixture of a deep black color and filled with carbonaceous matter. A foot or so beneath the surface the color is gray and the carbonaceous matter is less. At the bottom the wet mud is nearly white and there is little apparent carbonaceous matter. Wet muds at a depth of 2 feet contained 60,000 bacteria per gram, at 6 feet 2000 per gram, and at 8 feet 5000 per gram.[278] It is suggested that the microorganisms are dissipating the organic materials.

According to Collet,[279] one of the changes occurring in blue mud, a deposit rich in organic matter, is the taking of oxygen from the alkaline earth sulphates in solution, resulting in the formation of sulphides as expressed in the following equation:

$$CaSO_4 + 2C = 2CO_2 + CaS.$$

In the presence of water the calcium sulphide reacts with the carbon dioxide to form hydrogen sulphide and calcium bicarbonate, the latter combining with any excess calcium sulphide to form calcium carbonate and more hydrogen sulphide. The hydrogen sulphide, coming in contact with ferric

277 Moulton, G. F., Loss of red color in rocks, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 767–769; Keller, W. D., Experimental work on red bed bleaching, Am. Jour. Science, vol. 18, 1929, p. 65.

278 Bacteria analyses made under direction of E. B. Fred, Univ. of Wisconsin.

279 Collet, L. W., Les dépôts marins, 1908, p. 47.

oxide in the upper part of the mud, reacts therewith to form ferrous sulphide and sulphur. The equations which express these reactions are as follows:

$$CaS + 2CO_2 + 2H_2O = H_2S + H_2Ca(CO_3)_2$$
$$CaS + H_2Ca(CO_3)_2 = 2CaCO_3 + H_2S.$$
$$Fe_2O_3 + 3H_2S = 2FeS + S + 3H_2O_4.$$

If there is not enough ferric oxide or other substances in the mud to oxidize the hydrogen sulphide, it escapes into the water above, where it may form sulphuric acid, which reacts with any carbonate present in the water and forms sulphates. The iron sulphide formed in the mud is partly responsible for the blue color and ultimately changes to ferric sulphide through the addition of sulphur, the time of the change being unknown.

Some reactions lead to the formation of glauconite, others to phillipsite and various zeolites. Volcanic matter alters to a substance called palagonite,[280] and bentonite is an end product of the alteration of volcanic ash. These are considered on later pages. Sedimentary feldspars are probably products of diagenesis.

Lithification may be considered a part of diagenesis, although not a great deal is known about it. It is generally considered to result from cementation and recrystallization of the substances of the sediments; the permeating waters and the substances in solution therein being partly responsible. The weight of the overlying sediments is a factor in bringing about the lithification, probably having greatest influence in compacting finely divided sediments. That it is not the most important factor, however, seems indicated by the occurrence of unindurated sediments beneath many hundreds of feet of overburden. Nor is time a deciding factor, shown by the fact that some early Paleozoic sediments are unindurated, whereas undeformed sediments of much later time are well cemented. Too little is known as to the causes, times, and methods of cementation. It is a field inviting research.

Cementation results from deposition of one or more substances between the sedimentary particles. The cementing materials may be derived from the sediments cemented, from adjacent sediments, or from overlying waters. Sands of Bermuda dunes are stated to become firm in the basal parts of the dunes by deposition of calcium carbonate dissolved from the upper parts. Sands of the flood plains of some western rivers are cemented by materials deposited by circulating waters, these materials having been derived from unknown distances upstream. In the arid and semi-arid Southwest, surface materials are cemented by the deposition of salts (caliche) brought to the surface from below by capillary action, and very poorly cemented sand-

[280] Murray, J., and Renard, A. F., Deep sea deposits, 1891, pp. 299–300.

stone formations in the upper Mississippi Valley are made firm on the surface by the deposition of iron oxide, calcite, dolomite, or silica brought from the interiors of these formations in the same way, this cementation being known as case-hardening. For over a thousand miles on the coasts of Brazil there are sand deposits so strongly cemented as to resemble quartzite; these deposits usually lie transverse to mouths of streams and estuaries and have their summits at about sea level. Coral reefs, where present, are upon the seaward side. The cementing material is calcium carbonate, thought to have been deposited by fresh waters supplied by streams which the sand deposits restrained from freely entering the sea and compelled to pass by seepage through the sands, with deposition of calcium carbonate as a consequence.[281]

The chief cementing substances are calcium carbonate, silica, and iron oxide (or hydroxide). The second is frequently deposited in optical continuity with the crystalline silica composing some of the particles, thus in many instances changing the sand grains to particles with crystal boundaries, in others giving them new, but non-crystalline shapes. This is beautifully shown in parts of the St. Peter (Ordovician) and Cambrian sandstone formations of the upper Mississippi Valley. Cayeux gives sixteen varieties of shapes observed by him on enlarged sands of the Tertiary of the Paris Basin.[282] Lime sands have not been so extensively studied as those of quartz, but it seems probable that the particles are similarly enlarged. Other cementing materials are dolomite, siderite, pyrite, and marcasite, various hydrous silicates as some of the zeolites, prehnite, chlorite, epidote, serpentine, talc, and more rarely such anhydrous silicates as feldspar and hornblende. Van Hise[283] states that the Keweenawan sandstones of the Lake Superior Region have been partly cemented by feldspar deposited upon worn grains of that mineral, both orthoclase and plagioclase having thus been enlarged; and secondarily enlarged hornblende[284] has been found in old volcanic tuffs.

Recrystallization probably takes place to some degree in all rocks, but appears to be most effective in the more soluble, its greatest effects being shown in such rocks as limestone, gypsum, anhydrite, and salt. In some

[281] Branner, J. C., The stone reefs of Brazil, their geological and geographical relations; with a chapter on the coral reefs, Bull. Mus. Comp. Zool., vol. 44, 1904, pp. 1–28, 95 plates; also Bull. Geol. Soc. Am., vol. 16, 1905, pp. 1–12, pls. 1–11; reviewed by T. C. Chamberlin, Jour. Geol., vol. 12, 1904, pp. 748–752.

[282] Cayeux, L., Structure et origine des grès du Tertiaire Parisien, Paris, 1906, pp. 1–160 (111–113).

[283] Van Hise, C. R., A treatise on metamorphism, Mon. 47, U. S. Geol. Surv., 1904, p. 32.

[284] Grabau, A. W., Principles of stratigraphy, 1913, p. 755.

limestones this has gone on to such an extent that locally little remains in the rock to show the original character of the sediments, as instanced by parts of the Hoburgen marbles of Gotland and the Chicotte marbles of Anticosti Island. Recrystallization of gypsum may result in dehydration and formation of anhydrite, a change attended by 38 per cent decrease in volume. Certain conditions of recrystallization may lead to the development of the "porphyritic" gypsum occurring in the Permian of Kansas. Recrystallization of rock-salt deposits is stated by Grabau[285] to favor the development of a coarser texture. On the other hand, recrystallization of anhydrite may result in gypsum, a change known to occur when anhydrite enters the zone of ground-water circulation. This change increases the volume by 38 per cent. The latter is a case of alteration occurring after consolidation.

[285] Grabau, A. W., op. cit., p. 756.

CHAPTER III

IMPORTANT CONDITIONS MODIFYING SEDIMENTARY PROCESSES

Among the most important conditions modifying sedimentary processes are topography, climate, and migration of the shoreline. Topography to a considerable degree determines climate; the latter in its turn leads to modifications of the former. The topography of a land surface is chiefly responsible for stream velocity; this conditions stream competency and capacity; and shore topography determines to a large degree the sedimentary conditions in adjacent waters. Climate determines the quality and quantity of vegetation mantling a surface, and the two, climate and vegetation, determine very largely what sediments are produced and many of the characters they have when deposited. The position of a shoreline with respect to places on a sea or lake bottom largely conditions the depth of water at the place and the character and quantity of sediment deposited there; with migrations of shoreline, conditions and deposits change.

Influence of Topography

It has been pointed out that uncovered, steep slopes favor development of sediments due to block and granular disintegration, with the products of this origin generally dominating over those due to rock decomposition; whereas on gentler slopes an opposite ratio is favored.[1] It has also been noted that the agents of disintegration acting on bare rocks bring about the first result no matter what the topography, that a plant cover retards disintegration and favors decomposition, and that arid climates develop bare rock surfaces in regions of little or no relief.[2] Arid climates thus may produce results suggesting considerable topographic relief, whereas conditions of humidity may give results simulating those of little relief. These facts render determination of the conditions responsible for certain sediments more or less difficult.

The transportation that sediments undergo may so modify them as to suggest their having developed under more subdued topographic conditions, or more decomposing climatic conditions, than was actually the case, since

[1] Willis, B., Conditions of sedimentary deposition, Jour. Geol., vol. 1, 1893, pp. 476–480.

[2] Barrell, J., Relation between climate and terrestrial deposits, Jour. Geol., vol. 16, 1908, p. 168.

long transportation of sediments produced in a region of youthful topography may render them similar to the sediments produced in moist and warm low regions.

The most important element in topography so far as sediments are concerned is slope or relief. Elevation is important in that it is largely responsible for slope, high elevation generally, but not always, being characterized by steep slopes, whereas gentle slopes ordinarily are found in regions of low elevation. However, the sediments originating from a slope depend for their characters on the distance of transportation therefrom, and sediments derived from short steep slopes on low surfaces with little transportation are likely to be far coarser and less decomposed than those originating from a more extensive and steeper slope on a far higher surface distant from the site of deposition.

Many varieties of sediments are related in some degree to the topographies of the lands bordering the sites of deposition, and it is probably correct to state that this is the case for the conglomerates, sandstones, shales, limestones, cherts, and many others. Some of these form under certain topographic conditions and are wanting under others, the type of sediment being more or less intimately related to the topographic factor. In the early stages of the cycle of erosion, rock particles do not tarry long in the positions following their initial detachment. In later stages they move more slowly, and finally are carried only as the finest silts, colloids, and dissolved materials. When a region reaches the stage of mature peneplanation or old age, the subsoil in humid regions is completely saturated, contact between the rock minerals and meteoric waters is long maintained, decomposition becomes complete,[3] and only dissolved and colloidal materials are carried by the streams.

Following the plan of Barrell,[4] the relation of sediments to topography is considered from the points of view of topographic youth, topographic maturity, and topographic old age.

SEDIMENTS FROM HIGH REGIONS OF TOPOGRAPHIC YOUTH

High regions of topographic youth are characterized on their leeward sides by less moist conditions than on the windward sides, and the decrease in moisture tends to become greater from the summit downward. The precipitation may be partly rain and partly snow. The higher levels on both sides, in so far as they are not covered by snow or vegetation, are characterized by block and granular disintegration, and fine material tends

[3] Woolnough, W. G., Origin of white clays and bauxite: chemical criteria of peneplanation, Econ. Geol., vol. 23, 1928, pp. 887–894.

[4] Barrell, J., op. cit., pp. 166–170.

to be removed as rapidly as formed. Thus, fresh surfaces are constantly exposed to the work of frost, changes of temperature, and wind and water abrasion. These effects probably are greater on the leeward side and may increase in intensity downward, as the low precipitation does not favor growth of vegetation adequate to protect the surface. Slight leeward precipitation limits the development of glaciers and their deposits. Material produced on the leeward side is carried downward by temporary streams, landslides, mud flows, and winds, and lodged on the highland slopes, or on low areas about the base, forming alluvial fans which may coalesce to form continuous deposits extending over many miles. As the products result largely from rock-breaking, they contain little clay and have undergone little more decay than the possible oxidation of the ferrous iron, resulting in gray, yellow, brown, or red colors. The streams tend to flow in canyons; their coarsest materials are likely to be concentrated about canyon openings and to grade outward and downward into sediments of finer dimensions. The Great Basin side of the Sierra Nevada in places seems to approximate this condition, and similar conditions are thought to have existed along parts of the Atlantic Coast of North America during the deposition of the Triassic Newark series and in northern Great Britain when the Old Red Sandstones were deposited.

If vegetation occurs on the summit, or between the summit and the base of the leeward side, as is the case on parts of the east slopes of the Rockies in Montana and Wyoming, the Sierra Nevada, the Great Basin desert ranges, and elsewhere, this may serve to hold the loads of the streams, to a greater or less extent, and thus modify the results at the base.

To the extent that windward sides of mountains are above the snow line, materials are largely brought downward by glaciers and given to stream transportation or left in the valleys as ice deposits. If glaciers descend to the foot of a highland area, extensive deposits of outwash gravels are made, and the rock particles, because of the intense abrasion in the silt-laden waters, become rounded and generally lose the marks of glacial transportation. Below the snow line, under conditions of ample rainfall not characterized by cloudbursts, vegetation takes and holds possession of all surfaces which receive sufficient moisture and are not too steep to support such. This leads to maturity of rock decay and the accumulation of a soil over the surfaces so covered. This vegetation also holds materials falling from above. Undecomposed products which the streams obtain in the plant-covered areas are derived from abrasion of banks and bed, undermining of banks, earth and rock slides, and creep. The streams flow in canyons; the loads under conditions of glacial feeding may be large; and large alluvial fans may be built where the streams leave the highlands, or stream gravels may

be deposited for considerable distances down valleys. If there are no glaciers, the loads of the streams may be small and fans may not develop. Gravels tend to be better sorted than on the leeward sides and to contain more resistant material. Deposits may be little oxidized and contain some vegetable material, so that gray, blue, and dark colors obtain. If climatic conditions are such that plants are present in sufficient quantity to protect the surface, but not so abundantly as to prevent oxidation of the decomposed rock materials beneath, the loads carried by the streams may be red, yellow, or brown, and may retain these colors after deposition.

Plant-covered slopes of windward sides of highlands retain to a large degree the products of rock decay, their contributions to the streams being largely in the form of soluble and colloidal matter. Any condition diminishing, or eliminating, the plant protection leads to partial or complete removal of the decayed products, the change being expressed on the lowlands in increased rates of deposition and volumes of sand and clay, and these finer materials are usually succeeded upward by sands and gravels derived from the disintegration of the bed rock after the latter has been cleared of its soil. Conditions approximating the above may be seen on many of the mountains of the United States, where fire or close pasturage has bared bed rock to the work of frost and changes of temperature.

A climatic change leading to cloudbursts may also sweep the rock free of its protection, as the quantity of water falling at any one time may be beyond the absorptive capacity of the soil and mould, resulting in the exposure of bare rock surfaces over wide extent, so that the deposits on the lowlands may be like those resulting from the climatic change leading to a decrease of the vegetable protection. A change back to the original condition would restore the vegetable cover, and streams with decreased load would proceed to remove the deposits previously made on their piedmonts, leading in turn to an increased deposition on the flood plains and deltas.

A climatic change leading to elimination of glaciers from the higher parts of mountains would probably lead to the ascent of vegetation to higher elevations, with the result that draining streams would obtain a decreased load and would proceed to remove outwash, fan, and valley deposits previously made. This situation may be observed along the eastern and western fronts of the Big Horn, Bear Tooth, and no doubt other mountains. During the Pleistocene Ice Age the streams draining the Big Horn and Bear Tooth Mountains were fed by glaciers larger and more numerous than those now present, and immense deposits of gravel, sand, and silt were built along their bases. With the disappearance or decrease of the glaciers, the contribution to load from this source became very small, and the streams proceeded to remove the deposits previously made, and at the present time the es-

sentially clear streams reach the areas of earlier deposition with very limited burdens of suspended and tractional sediments and thus are able to degrade the earlier deposits. Restoration of extensive glaciers in the highlands would doubtless restore conditions of aggradation about the feet of the mountains.

Intimately connected with the characters of the sediments derived from regions of physiographic youth is the deformative movement to which the elevation is due. A region in orogeny passes through the stages of its early uplift, attains the period of maximum movement, and is worn down after orogeny has come to an end and during the closing stages of deformation. Shales, sandstones, conglomerates, and breccias derived from a region while it is thus being deformed may be designated as *orogenic*.

Extending along the north side of the Alps for many miles is a remarkable series of marine and continental clastics known as the Flysch. The age seems to be mainly, if not entirely, Cretaceous. These clastics were deposited as the Alps were rising. Higher in the section is a Tertiary series of marine and continental clastics known as the Molasse of which the composing materials are thought largely to have been deposited during and after the time of most pronounced movement. The Flysch and Molasse basins of deposition did not coincide, the former having been laid down in a basin or geosyncline near, and in part under, the northern edge of the present mountains, the latter in a basin or geosyncline north of the Flysch basin.

These two stratigraphic divisions of the Alpine section have been given generic significance by van der Gracht[5] who defines *flysch* as an orogenic deposit laid down in a geosyncline directly previous to the major elevation, when the initial diastrophism had already developed interior ridges exposed to erosion. The basin of deposition may range from shallow to deep and the environment from marine to continental. The sediments tend to range from fine clastics below to coarser above. The *molasse* represents "detritus worn from elevated ranges during and immediately posterior to the major diastrophism, deposited in a *later* foredeep, considerably in front of the preceding flysch geosyncline." Van der Gracht interprets the late Mississippian and early Pennsylvanian clastics about the Ouachita Mountains of Arkansas, Oklahoma, and Texas as orogenic deposits of flysch aspect and the middle and late Pennsylvanian clastics laid down in a somewhat different basin as having the aspect of molasse. This view without the use of the

[5] Van der Gracht, W. A. J. van Waterschoot, The Permo-Carboniferous orogeny in the south-central United States, Verhandelingen der koninklijke Akademie van Wetenschappen te Amsterdam, 1931, pp. 9–10; also see Jour. Geol., vol. 39, 1931, pp. 697–714.

European terms had been previously more or less expressed by Cheney.[6] Van der Gracht names other deposits which he considers of flysch and molasse aspect.

The differences in the materials of flysch and molasse sediments are that those of the former range from fine clastics below to coarser above and are more or less deformed, whereas the materials of the molasse range from coarse clastics below to finer above and are not at all, or very little, deformed. If orogeny has been accompanied by overthrusting it may come to pass that parts of the flysch will lie below the thrust sheets or nappes and this over-ridden flysch may contain blocks from rocks found in the overlying thrust sheets, or from terranes concealed by the overthrusting. The first type of blocks is said to exist in the wildflysch of the Alps and van der Gracht has explained the blocks in the "Caney" shales of Oklahoma as not due to deposition from floating ice, but as having been derived from terranes buried beneath the flysch and the over-riding thrust sheets.

SEDIMENTS FROM REGIONS OF TOPOGRAPHIC MATURITY AND LOW REGIONS OF TOPOGRAPHIC YOUTH

In regions of topographic maturity and low regions of topographic youth, the greater portion of the surface is of such lowness that elevation is not an important factor of climatic control, and the slopes are mainly of such inclination as to support a plant cover correlative to the climate. Under conditions of abundant rainfall, an excellent protective plant mantle develops, areas of exposed rock are largely eliminated, and, except locally, rock decay attains maturity. The relief may lead to considerable fluctuation of the water table, with correspondingly greater leaching, and decay may extend to great depths. Streams flowing from regions of this character bring to the sites of deposition little other than the finest of sand, silt, and clay; and these, due to the abundance of vegetation, as a rule have had their iron largely reduced and have been more or less mingled with carbonaceous matter, so that gray and blue colors dominate. Essentially all the sediments are carried to the places of relatively permanent deposition, provided the streams do not flow through an arid or semi-arid region.

A mature or low youthful topography in a region of intermittent rainfall supports a moderate plant covering, but in most places one that is adequate to promote mature decay. There may, however, be places of exposed rock. The iron in the decayed rock is changed to the insoluble oxide or hydroxide

[6] Cheney, M. G., History of the Carboniferous sediments of the Mid-Continent oil field, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 557–594; Stratigraphic and structural studies in north-central Texas, Univ. Texas Bull., no. 2913, 1919.

(this being favored by warmth), which usually remains with the soils, giving them yellow, brown, or red colors. During times of heavy rainfall, considerable quantities of soil and some undecayed materials are brought to the streams of the region, the waters becoming yellow to red as a consequence and maintaining this color for many miles, as shown by the Red, Pecos and other southwestern rivers. The fate of the sediments depends on the subsequent courses of the streams. If they flow through a region of wetter climate, the sediments pass through changes leading to reduction of the iron. Parts of the sediments may be deposited on the flood plains, and parts are carried to the deltas, where each flood season may be indicated by a bed of gray, blue, or dark silt and clay, succeeded and preceded by a thin bed of fine silt and clay representing the periods of lower water. If the streams flow through dryer regions, aggradation prevails, the valleys become filled, and, if possible, the sediments still more oxidized. The deposits over the flood plains and deltas then consist of red, yellow, and brown sands, silts, and clays. Some of the Red Beds of the Western States are thought to have developed under these conditions.

Under conditions of slight rainfall, Huntington's description of the mountains of Persia applies, where "the prominent characteristic . . . is the nakedness, roughness and sterility" of the surface.[7] Rock breaking dominates over rock decomposition, with the result that the products largely reflect the characteristics of the mother rock. The streams are temporary and do not have sufficient water to carry the sediments out of the region, but deposit them as alluvial fans, valley fills, and in the more or less ephemeral lakes, the streams in many instances losing themselves in their own deposits. All sizes of fragments occur, even to very large, the coarsest being near the upper borders of the basins and the finest silts in the temporary bodies of standing water. There is little clay.

It is thus seen that the sediments from regions of mature topography range from the dissolved, colloidal, and fine suspended matter given by plant-covered areas to the coarse mechanical sediments of regions without protective plant cover.

SEDIMENTS FROM REGIONS OF TOPOGRAPHIC OLD AGE

Topographically old regions may range from arid to humid. Humid regions have sluggish streams of low competency and capacity, whose loads ordinarily consist of dissolved and colloidal matter with small quantities of suspended and tractional matter, the latter largely derived from erosion of banks and bed and rather thoroughly decomposed. Considerable matter

[7] Huntington, E., Explorations in Turkestan, Publ. no. 26, Carnegie Inst. of Washington, 1905, pp. 247–248.

of organic origin is also likely to be carried. The deposits made by streams consist of fine-grained clays and silts as a rule rich in carbonaceous matter, and very small quantities are brought to the sea, the rate of deposition thus being very slow at the mouths of streams.

Topographically old arid regions have essentially all erosion performed by wind, the surfaces being too flat to give much velocity to the small quantity of water occasionally falling. Deposits previously made have been removed, the area being a rock floor overspread with a thin veneer of lag gravels, a generalization first made by Passarge[8] and subsequently elaborated by Davis.[9] In a region of this character little in the way of sediments may be expected to be deposited that will endure; the matter derived from and deposited without the region would in no way be distinctive.

SEDIMENTS AND SHORELINE TOPOGRAPHY

A close relation exists between the topography of a shoreline, and the sediments deposited in adjacent waters and the organisms dwelling on the bottom whose remains ultimately become sediments. Following Johnson,[10] shorelines are classified as submergent, emergent, neutral, and compound.

Shorelines of submergence have brought the waters over a former land surface which may have been in youth, maturity, or old age. Submergence over a youthful surface develops deep bays and long headlands with deep waters near the shore. The waves, having immense power, rapidly develop cliffs on the exposed parts and drag material to the heads of the bays, which may be more or less filled, with the bayhead advancing seaward. Large quantities of sediment are carried down the slopes away from the shore. Bottoms near the shore show great variation in type of sediment from place to place. Organisms live in abundance in protected places in the bays; few or none live on the strong current- and wave-swept bottoms. This is the time of greatest transportation and also of transportation of the maximum dimensions of materials, as the steep slopes adjacent to the shore permit large fragments to be carried outward and possibly deposited in the midst of finer material.

With progress toward maturity, a profile of equilibrium develops, a wave-cut platform is eroded, and the waves lose in ability to erode the shore, as much of their energy is required to travel over the bottom. Less and less material is transported, and that transported is of decreasing dimensions;

[8] Passarge, S., Über Rumpfflächen und Inselberge, Zeits. d. deut. geol. Gesell., vol. 56, 1904, pp. 193–209.

[9] Davis, W. M., The geographical cycle in an arid climate, Jour. Geol., vol. 13, 1905, p. 393.

[10] Johnson, D. W., Shore processes and shoreline development, 1919, p. 172.

a greater uniformity of distribution is obtained; and there is less and less variation in the sediments from place to place. Bottom faunas become more uniform.

Ultimately old age is attained on both shore and adjacent land, and the waves reach the shore with little power to erode. The wave-cut platform has been eroded deeper and swept clean of materials, and the deposits of the early portion of the cycle are partly planed away (see fig. 3). Absence of sediment in the waters permits organisms to live in immense numbers in the shallow waters below tide. The shore now has its headlands gone, and its position may be far inland from the bayheads of its youth. A great deal of the deposits of the earlier stages has been transported outward and deposited in deeper waters, and a submarine eroded surface exists over those which remain.[11]

This shore may be again submerged and later deposits made over the submarine eroded surface, these deposits resting unconformably upon those of the earlier submergence; and a similar sequence of conditions may be developed for each submergence, each unconformity representing, not uplift, as commonly postulated, but depression.

Submergence of a shore of low relief brings waters over a surface which may be of so little inclination that the new bottom will be flatter than the profile of equliibrium for the conditions, and thus the waves will be compelled to break at some distance from the shore, and possibly barrier beaches may form. The latter are, however, ephemeral and will later be removed in the same way as outlined for shorelines of emergence. As shores are submerged and shorelines move landward, distances between sea level and places on the previous bottom are increased, with changes of sediments and faunas at each place, and with probable deeper-water conditions migrating shoreward, producing overlap in that direction.

The youthful stage of shorelines of emergence has the water's edge in contact with a portion of an original sea bottom. As the profiles of sea bottoms at a distance from the shore are of low inclination, the waves have little power to erode the shore, and the probabilities are that parts of the bottom are above the profile of equilibrium correlated with the conditions. Some erosion of the bottom materials is certain to occur unless the elevation of the shore and adjacent land has so stimulated stream transportation as to bring to the sea quantities of sediments beyond the disposition capacity of the waves and currents. Barrier beaches may be erected at some distance from the shore. These ultimately will be subject to erosion on their seaward side, and they may be extended on their landward side. Back of the barriers are lagoons in which wave and current activities are weak. Tidal

[11] Johnson, D. W., op. cit., p. 246.

currents carry sediments into the lagoons from the sea, and streams bring contributions from the land. Some sediments are blown from seaward to the land sides of barriers, and others may be brought over the barriers by waves. The quiet and protected waters of lagoons favor colonization by organisms, and if the waters are not turbid too frequently and of normal salinity, it may be expected that abundant plant and animal life will flourish on the bottoms. Through organic and inorganic agencies, lagoon bottoms ultimately are brought to depths at which an abundant growth of plants takes possession and salt marshes ultimately result. A barrier may migrate landward across its marsh and bring its outer shore to the landward side of the former lagoon,[12] with consequent erosion and disappearance of all previous deposits, in so far as they are above the profile of equilibrium determined by the conditions. If sea level remains stationary, the shore will continue to move inland and the bottom ultimately will be cut to the base level of deposition.

Seaward, beyond the point where the level of the profile of equilibrium rises above the bottom, deposition will have continued as it did previous to the rise of the shore and probably will have increased; but distances between sea level and places on the bottom will have decreased, and there will have been migration of sediments and faunas seaward to depths adapted to their character, with consequent overlap, or outlap, of deeper water sediments and faunas by those of shallower water.

Neutral shores are those of delta fronts, alluvial fan fronts, outwash fronts, about coral reefs, and fault shores. Each of these is a particular problem, but the first three have more or less the same characteristics so far as sediments are concerned, and are considered in connection with other topics. Coral-reef shores are considered in connection with coral reefs, and fault shores yield sediments more or less like those of shores of submergence. Compound shores are those which show both emergence and submergence and yield sediments like those of one or the other condition depending on which movement was the last to occur.

SUMMARY

Too great a relation must not be assumed to exist between the sediments which may be deposited and the elevation of the surface from which they come. Streams entering the sea from areas of relatively low relief may contribute either coarse or fine material, depending on the length of transportation and the effectiveness of the vegetable cover. Streams from regions of high elevation may contribute either gravel or silt for the same

[12] Johnson, D. W., op. cit., pp. 258–262.

reasons. That high elevation and great relief do not necessarily mean coarse sediments is shown in the Fraser River of British Columbia, the greater part of whose deposits over its delta is composed of sands with dimensions ranging from 0.25 to 0.5 mm. Gravel particles up to about 0.5 inch in diameter were found in a few places in the main channel. This stream has strong freshets which average 18.5 feet and in 1894 reached a maximum of 25.75 feet, and the currents are strong, but only small quantities of gravel are present, and for their transportation appeal has been made to driftwood or floating ice. Near the mouth the deposits appear to be wholly sand and silt, and only very fine sediments are brought to the sea.[13] In spite of the fineness of the deposits, however, it is only about 50 miles up the river to the mountains; the river takes its rise on a high plateau and in snow-covered mountains, flows through a deep canyon, and is eroding extensive glacial deposits.

It has been assumed that during times of great continental relief the sediments produced on the land are coarse and gradually change to dissolved and colloidal matter as erosion reduces the land to base level. Relative rising of the base-leveled land with respect to sea level is assumed to reverse the above sequence of sediments transported. In the early stages the near-shore deposits are assumed to have been sandy, succeeded outward by muds, and the latter followed seaward by calcareous bottoms. As the land becomes lowered through erosion, the mud and calcareous belts migrate landward to overlap the sediments previously deposited there, and as uplift succeeds stability, the shoreward belts migrate seaward to overlap, or outlap, previous deposits in similar fashion.[14] That sequences of this character obtain in some divisions of the geologic column suggested to Hall and Newberry[15] the idea of *circles of sedimentation.* It was assumed that the coarse sediments in the basal part of the sequence represented deposits made on and near a shore. Advance of the sea led to the coarse sediments being succeeded by muds and these in turn by calcareous sediments. Retirement of the sea produced the same sediments in reverse order. Willis[16] explained a sequence of sediments of this kind in terms of the cycle of erosion; a "sand base, a limestone middle and shale top," denoting respectively youth and maturity, old age, and rejuvenation.

It is thought that the "circle" or cycle of sedimentation, as used in this connection, may be maintained only in a very loose sense. It is of course

[13] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv. Canada, 1921, pp. 8, 31–33.

[14] Wilson, A. W. G., The theory of the formation of sedimentary deposits, Canadian Rec. Sci., vol. 9, 1903, pp. 112–132.

[15] Newberry, J. S., Circles of deposition in American sedimentary rocks, Proc. Am. Assoc. Adv. Sci., vol. 22, 1873, pp. 185–196.

[16] Willis, B., Conditions of sedimentary deposition, Jour. Geol., vol. 1, 1893, p. 180.

true that sediments transported from regions of considerable elevation are likely to be coarser and more abundant than those from regions of little elevation. Much depends on the condition of a region prior to uplift. Greater quantities will be received from regions which prior to uplift were covered with deep residual soils or other loose and fine materials. Such conditions, given agents of transportation, would yield great thickness of sediments over parts of the sites of deposition, and the sediments would be more apt to be fine than coarse. At any rate, finer materials would dominate in those first transported, and after these were removed, coarse sediments might follow if the sites of erosion or distributive provinces were not protected by plant cover and were not too distant from the sites of deposition. Thus the assumed sequence of sediments might be in reverse order. The thickness of sediments, considered from the point of view of the duration of their deposition, seems to be a better measure of the extent of uplift than is their coarseness, and even this might fail, since a large river draining a land of moderate relief would be likely to supply a greater volume and thickness of sediments in a given interval of time than could come from a much higher, but smaller, land. If a land of moderate relief were heavily mantled with vegetation, had its shores composed of resistant rock, and had shallow waters about its shores, neither the shores nor the land surface would yield a large volume of clastic sediments, and calcareous deposits might be built to the beach; whereas a lower land with moderate growth of vegetation, with its coastal rocks yielding readily to wave attack, with rainfall adequate to carry sediments to the sea, and with sufficient depth of water adjacent to the shore to permit wave attack, would yield much larger volumes of sediment to the sites of deposition. It has been suggested that as the early Silurian deposits of eastern North America are not very coarse, the evidence of the sediments does not support the view of a great uplift at the close of the Ordovician.[17] This view may be correct, but it is thought that the thickness of the late Ordovician and early Silurian deposits and not their coarseness is the most important fact with respect to the problem.

Another fact bearing on the relation between topography and sediments is found in the variety and stability of the allothogenic, or detrital, minerals in a sedimentary deposit. A high land subject to vigorous erosion would as a rule contribute a greater variety of minerals than a lower land, which would be more likely to be covered with a deep residual soil. The sediments from the first described land, moreover, would probably contain many more minerals of medium and little stability than those from the latter.[18]

[17] Clark, T. H., A review of the evidence for the Taconic revolution, Proc. Boston Soc. Nat. Hist., vol. 36, 1921, pp. 157–158.

[18] Boswell, P. G. H., Trans. Geol. Soc. Glasgow, vol. 18, pt. i, 1926–27, p. 143.

Sediments and Climate

The effects of climate are both direct and indirect. The direct effects are felt by sediments from the time of production to consolidation. As sediments may originate in one climate, be transported through another, and be deposited in a third, the climatic impress may be a composite one of which the components of the climate of origin and those of transportation may hardly be apparent. This is exemplified by some of the sediments carried by the Missouri-Mississippi system, part of which originate under the glacial conditions of the high Rockies, are transported through the semi-arid regions of the Plains and the intermittently rainy regions of the central Mississippi Valley, and are deposited in one of the rainiest parts of the United States; and when finally deposited they have largely lost the characters given by the various climates except those of the regions of deposition and the last transportation. Certain broad generalizations are, however, possible. The Mississippi River, originating in the Temperate Zone, brings prevailingly gray sediments to the borders of the Tropics, but those of the tropical Amazon are prevailingly red,[19] those of cold Alaska dark,[20] and those of glacial streams light colored.

Indirect effects of climate are due to vegetation, for whose presence or absence climate is largely responsible and to whose presence maturity of rock decay is chiefly due.

Continental sediments show the climatic conditions of origin better than marine ones. This arises from the generally short transportation of the former, with the climate of the place of origin similar to that of the place of deposition. The effects of climate are well shown through comparison of the sediments of an alluvial fan of our arid Southwest with one of Newfoundland, or a lake deposit made in the Great Basin with one of eastern Canada.

The allothogenic or detrital minerals of continental sediments are important for their application to interpretation of climatic conditions of origin. An abundance of feldspars[21] and a commonness of ferro-magnesian minerals suggest conditions unfavorable for decomposition, but they do not prove aridity.[22] The occurrence of the same minerals in marine sediments, on the other hand, has no bearing on climate, as they might result from shore erosion.

The color of sediments also has great bearing on the question of climate,

[19] Walther, J., Einleitung in die Geologie, 1894, p. 815.

[20] Blackwelder, E., The climatic history of Alaska from a new viewpoint, Trans. Illinois Acad. Sci., vol. 10, 1917, pp. 275–281.

[21] Mackie, W., The feldspars present in sedimentary rocks as indicators of climatic conditions, Trans. Edinburgh Geol. Soc., vol. 7, 1899, pp. 443–468.

[22] Reed, R. D., The occurrence of feldspars in California sandstones, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 1023–1024.

but caution is necessary, as different rocks in the same climate may produce different colors. In Texas the Taylor and Navarro formations give brown and black residual soils and flood-plain deposits, whereas the Wilcox, Mount Selman, and Cook Mountain formations give buff or red decomposition products in the same environment, the vegetation in each case being essentially the same. The difference in color arises from the smaller quantity of iron[23] contained in the former. The intimate effect of climate upon the colors of soils and ultimately upon sediments is shown by the following experiment carried out in the soil experiment stations of California, Kansas, and Maryland, soils from Kansas and Maryland being transported to California, Maryland and California soils to Kansas, and Kansas and California soils to Maryland. The Kansas and Maryland soils in their California location became a deeper red, and the California and Kansas soils in Maryland bleached to a light or yellow gray.[24] The California soil in Kansas changed from a distinct red brown to a darker red brown and in Maryland to a dirty gray. The Maryland soil in Kansas changed from a light brown color to a deep dark brown and in California to a reddish brown. A black-brown soil of Kansas changed to light brown in California and to light ashen gray in Maryland. Each of the soils was taken from the upper foot, and the experiment extended over seven years. There were also changes in the contents of the silica, potash, lime, iron, alumina, and other constituents.

Glinka[25] placed such high value upon climate in soil formation that it was used as a basis for his classification of those soils which he designated as ectodynamorphic, that is, soils for whose origin external factors were largely responsible. His classification of the ectodynamorphic soils is as follows.

1. Soils developed under optimum moisture conditions. Soils low in humus, leached, composed largely of the oxides and hydroxides of silicon, iron, and aluminum, colors yellow to red. Laterite, terra-rossa, yellow soils.
2. Soils developed under moderate moisture conditions. Oxides of iron removed, silica remains, soils usually leached, colors light. Podsol soils, gray forest soils, degraded tschernosum.
3. Soils developed under moderate moisture conditions. Soils contain much carbonate, much sulphate, much humus, colors dark to black. Tschernosum and regur?, the black soil of India.
4. Soils developed under insufficient moisture conditions. These are the soils of the dry prairies. They have low humus, and lime carbonate and sulphates are

[23] Hager, D. S., Factors affecting the colors of sedimentary rocks, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, p. 919.

[24] Lipman, C. B., and Wayrick, D. D., A detailed study of the effects of climate on important properties of soils, Soil Sci., vol. 1, 1916, pp. 5–48.

[25] Glinka, K. D., The great soil groups of the world and their development, English transl. by C. F. Marbut, 1927, pp. 35–42.

universal constituents; silicates not thoroughly decomposed, and colors range from gray to brown or red.

5. Soils developed under excessive moisture conditions. These are the peaty soils and they have black colors.
6. Soils developed under temporarily excessive moisture conditions. These are the alkali soils, and they contain large quantities of such easily soluble salts as sodium sulphate, sodium carbonate and bicarbonate, etc.

The following diagram from Lang (fig. 12) gives in graphical form the inter-relations of soil character, temperature, and rainfall. It should be

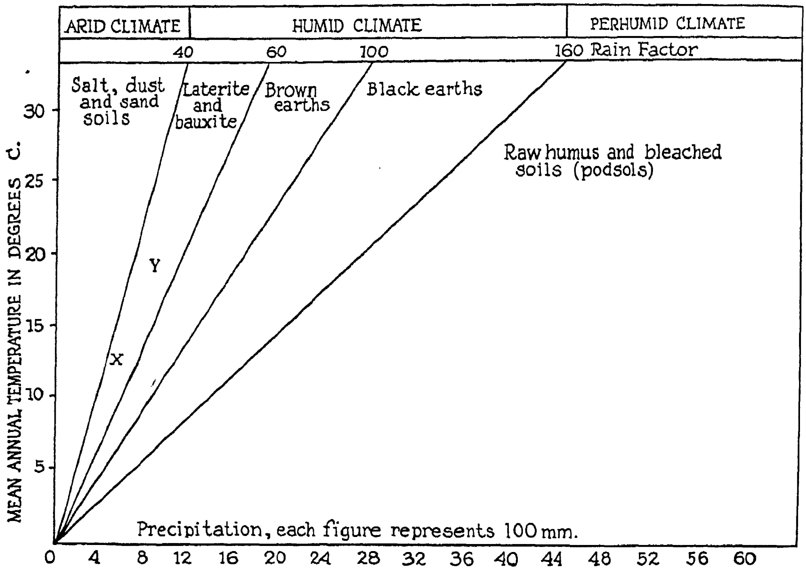

FIG. 12. DIAGRAM SHOWING INTERRELATIONS OF SOIL CHARACTER, TEMPERATURE, AND RAINFALL

The letters *Y* and *X* represent red and yellow soils respectively. After R. Lang, Verwitterung und Bodenbildung als Einführung in die Bodenkunde, Stuttgart, 1920, p. 119.

noted that soil character varies directly with respect to both rainfall and temperature. The extent of cloudiness and of wind are also factors in that both affect the quantity of water retained by the ground.

Climates may be classified as those which are frigid, those which maintain a wet substratum throughout the growing season and have no dry seasons, those which have the substratum intermittently wet, those which are semi-arid, and those which are arid. This departs somewhat from Barrell's[26] classification of constantly rainy, intermittently rainy, semi-arid,

[26] Barrell, J., Relations between climate and terrestrial deposits, Jour. Geol., vol. 16, 1908, p. 255.

and arid. The term rainy does not exactly meet the conditions, as the important factor, so far as the sediments are concerned, is the maintenance of a wet substratum, accomplished by intermittent rains under some conditions of temperature and cloudiness and by constant rains under other conditions. This is illustrated by the fact that the Island of Anticosti, with the same rainfall as northeast central Texas, supports a rank growth of vegetation on a substratum that rarely dries out, whereas that part of Texas has only a limited growth of vegetation and a substratum which is dry much of the time.

The subject is considered first as to the effects of climates on continental sediments and secondly with respect to marine sediments.

SEDIMENTS FROM REGIONS WITH FRIGID CLIMATES

Regions with frigid climates have the surface permanently frozen most of the time, are subject to frost every night of the year, and have the surfaces more or less permanently covered with snow and ice. The materials brought to deposition are almost wholly of mechanical production, resulting from rock grinding and abrasion, glacial plucking, and block and granular disintegration through frost action and changes of temperature. The deposits are largely made by ice and melt waters and consist of undecomposed materials, both fine and coarse, the latter particles angular to subangular where not modified by water, and occasionally marked by the striæ characteristic of glacial transportation. The surface upon which the deposits rest may also be striated.

Minerals are not apt to have experienced much decomposition. Samples of sands collected by Mr. R. J. Lund at Chesterfield Inlet on the northwest margin of Hudson Bay are filled with feldspar and ferromagnesian minerals, have nearly all particles angular and little polished, and are not well sorted. The limited or abbreviated water transportation in regions of frigid climates does not favor rounding or sorting.

Where a frigid climate obtains over a plain, glacial and aqueo-glacial deposits are about the only ones made, and essentially all materials have been obtained by ice. In alpine regions under the conditions of frigid climate, the deposits contain much material which is the result of block and granular disintegration for whose production ice was not responsible, and some of this may have slid directly to the places of deposition.

Ground and broken rocks are prevailingly of light colors, and the deposits which contain these as important constituents are light in color unless changed by the entrance of other material. As glacial ice ultimately reaches a lower region or a warmer climate or both, its load is ultimately given to water. If this water is cold and the transportation short, little decomposition

results and the sediments retain their light colors. These deposits may dovetail with those of less frigid conditions. The intense grinding that takes place in the heavily silt-laden waters of glacier fronts rapidly obliterates the marks of glacial transportation, shown by the rare occurrence of striated pebbles in fluvio-glacial deposits and by the general rounding of the pebbles. Thus, the gravels beyond a glacier front may show little evidence of glacial transportation. Farther outward, glacial gravels may be expected to be succeeded by light-colored sands and clays of which the constituents show little decomposition.

Frigid climates cover extensive areas of the present earth's surface and such must have been the case during many times of earth history. Sediments derived from frigid climates are being deposited in the seas around Antarctica and its margining islands, Greenland, the north parts of North America and the Euro-Asiatic continent, and the Arctic Islands.

SEDIMENTS FROM REGIONS WITH CLIMATES WHICH MAINTAIN A WET SUBSTRATUM THROUGHOUT THE GROWING SEASON AND HAVE NO DRY SEASONS

Vegetation abundantly covers the surface where a climate of this character obtains, since the ground remains permanently soaked with water because of high ground-water level or constant rainfall. Here plants grow with wonderful luxuriance, their roots being constantly bathed in water; and on death they fall on a wet surface, where they may remain to function as a sponge to raise the water level still higher.

Surfaces of this character are not necessarily flat, but may have steep slopes; the latter, however, favor drainage, with the consequence that wetness is maintained with greater difficulty and there is much underground circulation of water.

Great areas of the present surface of the earth have climates of the above character, particularly on the polar sides of the temperate zones, as a far lower rainfall is adequate to maintain a wet substratum there than in the more tropical regions. Such areas are widespread in north Europe and Asia. Much of Ireland and Newfoundland[27] also meet the condition, as do large tracts in Canada. Further extensive areas exist in Florida[28] and other parts of the Gulf and Atlantic coastal plains, central Africa, certain parts of the Amazon Basin, and other flat wet lands in the Torrid Zone, and there are large areas around many high regions of both the Temperate and Torrid zones.

Where a high water level obtains in a warm climate and the surface has

[27] Perley, M. H., Canadian Nat. Geol., vol. 7, 1862, pp. 321–334.

[28] Harper, R. M., Preliminary report on peat, 3rd Ann. Rept., Geol. Surv., Florida, 1910, pp. 199–375.

little relief, the rain water soaks downward from the surface and moves laterally near thereto. There is little or no ascent of ground water through capillary action and hence no deposition of dissolved salts in the surface materials. Processes of decomposition are retarded and are thought to extend to slight depths with only a thin mantle of weathered material produced. This mantle may be expected to have been leached of all soluble materials and thus to be low in alkalies, lime, and magnesia. Most of the iron and some of the alumina have probably been removed, the former as colloid and carbonate, the latter as colloid, and some of the silica will also have been taken away. If minerals containing sulphur are present, or the soil contains sulphur compounds, bacteria may reduce them, forming hydrogen sulphide whose presence is "likely to facilitate removal of the iron."[29] The soil mantle may be predicated to be composed of extremely resistant materials such as quartz, hydrous aluminum silicates, and resistant minerals derived from parent rocks. The nearer the surface approaches base level, the more nearly will the soil mantle approximate the above composition, and "If the residual material consists entirely of the most insoluble products of rock weathering, a uniformly moist climate may be postulated during the last stages of peneplanation."[30] It is certain, however, that in regions of low temperature rock decay may not be so complete, and thus the surface materials in considerable part may be the result of rock disintegration, but the depth of such would also be slight.

The slight depth of rock decay and breaking is shown by the polished rock surfaces which have persisted small distances beneath the surface since the departure of the Pleistocene ice. Such have been described from Finland and the Urals by Von Richthofen,[31] and may be seen over many parts of North America.

The colors of residual materials produced under the conditions described range from black to white. The black arises from contained organic matter and is associated with the surface materials. The light-colored residual materials are beneath the surface and contain only small quantities of organic matter. Deposited materials as a rule contain much organic matter and are dark.

Sediments derived from regions heavily covered with vegetation will consist largely of organic, colloidal, and dissolved substances. Under warm conditions, and to a less degree with decreasing temperatures, pelagic sediments may be expected to be deposited in shallow waters adjacent to

[29] Moulton, G. F., Loss of red color in rocks, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 767–769.

[30] Woolnough, W. G., Econ. Geol., vol. 23, 1928, pp. 887–894.

[31] Richthofen, F. von, Führer für Forschungsreisende, Berlin, 1886.

the beach. Except for such organic deposits as peat, sediments of continental deposition will be of little importance. No sediments will show effects of desiccation to any marked degree.

Climates of the type considered exist around and over some elevated areas of the earth's surface, where they may be marginal to glacial environments and areas of pronounced rock disintegration. Products of this disintegration and glacial débris, if glaciers are present, with the residual materials arising from the climatic conditions, become more or less bleached because of the abundance of vegetable matter; and mica, feldspar, and other minerals of fair stability do not experience complete decomposition, but are deposited with other sediments correlated with their dimensions and weights. Alternating units of gray micaceous shales, gray arkose, and carbonaceous materials may therefore occur in the same sequences.

Lands of which the substratum is wet because of constant rain may have a deep water table and support luxuriant vegetation, but with a deep water table they are not likely to have a thick protective cover of dead vegetable matter. As water is constantly passing downward, carrying vegetable matter and carbon dioxide, the rock is decomposed, and all the soluble constituents may be removed. The residual soils which remain and the sediments which are derived therefrom contain no, or very small quantities of lime, magnesia, soda, potash, and possibly iron.[32] They may have red colors.

SEDIMENTS FROM REGIONS WITH CLIMATES WHICH MAINTAIN A WET SUBSTRATUM A CONSIDERABLE PART OF EACH YEAR AND HAVE DRY SEASONS

Barrell has used the term "intermittently rainy" for this type of climate, but it is believed that the above characterization better fits the conditions. Rain may not fall for weeks at a time, and the soil each year becomes thoroughly dried and cracked one or more times. This condition restricts vegetation and more or less destroys its effectiveness as a cover. The lower lands under uncontrolled conditions are forested, and such may also be true of the upper lands, but there is excellent drainage, and the water table is low. Vegetable matter does not accumulate except very locally in the sloughs of the flood plains. Oxidation of the soils of the uplands is fairly complete, and the iron is usually in the form of the oxide or hydroxide and remains with the soil, which becomes yellow or red, like the soils of northwestern Louisiana, parts of Virginia, etc., forming in tropical and subtropical regions such soils as the laterites. Regions of the above type of climate

[32] Merrill, G. P., Rocks, rock-weathering and soils, 1906, p. 357.

may support much adapted vegetation, but if it is sufficiently warm and underground drainage is good, little vegetable matter accumulates. According to Hager, the iron in a warm moist climate is in the form of limonite.[33] Under some conditions of intermittent rainfall and temperature and limited vegetation, organic matter does accumulate in the soils, which become black as a consequence, like the tschernosum soils of Russia. These seem to form toward the dryer end of these climatic conditions.

The carbonates of lime, magnesia, soda, and potash tend to be removed from the places of good drainage. In the poorly drained areas, soluble materials tend to accumulate in greater or less quantities, some of which may be observed as white films over the flood plains after the water has evaporated. Also, small iron oxide and lime concretions are formed in the soil and may ultimately wash into the deposits.

During dry seasons the ground, if materials permit, cracks to greater or less depths; these cracks facilitate the passage of surface waters and atmospheric gases downward, and as ground-water level is generally low, these surface waters bring the processes of decomposition far beneath the surface, and decomposition may become mature for long distances therefrom. Not all of the soluble and colloidal matter is carried laterally. During the times of desiccation some of it is moved to the surface by capillary action and precipitated as the carrying water evaporates. Both, and particularly the colloids, are precipitated commonly around nuclei to form concretions of concentric structure and greater or less dimensions. As hydroxides of iron and aluminum are most colloidal when precipitated from cold and dilute solutions, these substances may be extremely common in the subsoil.[34] The waters which sink into the soil following the next rainfall tend to approximate in hydrogen ion concentration the character of the waters which precipitated the colloids; hence, these are not likely to be taken up by the descending waters, and ultimately there is formed a crust of amorphous, more or less concretionary material on, or beneath, the surface, consisting chiefly of alumina, iron oxide or hydroxide, and amorphous silica, resting on a substratum of insoluble residual constituents. Conversely, a crust and substratum of this kind denote the climate of intermittently wet and dry conditions.

During seasonal freshets streams may cover their flood plains and leave temporary lakes in depressions, with a population of fish and other animals received from the streams, and toads and frogs later deposit their eggs

[33] Hager, D. S., Factors affecting the colors of sedimentary rocks, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, p. 921. Probably one or other of the various hydrous forms of iron oxide generally known as limonite.

[34] Woolnough, H. G., Econ. Geol., vol. 23, 1928, pp. 887–894.

therein. Also, during freshets the stream waters are yellow or brown with mud, and considerable quantities of vegetable matter are transported and deposited over the flood plains with clay, silt, and sand, or carried to a permanent body of water and incorporated in the sediments there deposited. Parts of the clays and sands retain their yellow and brown colors until burial, and these colors may become deeper with each drying. Barrell has suggested that consolidation also leads to a deepening of color.[35] The vegetable matter deposited with some of the sediments tends to reduce the oxides of iron to the carbonate, with consequent leaching and the production of gray and blue shades. The deposits of the sloughs and swamps have dark and blue colors due to the incorporation of organic matter, and locally there may be considerable peat. As there may be areas of rock surfaces undergoing disintegration, it is probable that the products therefrom may from time to time be deposited with the finer decomposed materials. These disintegrated products also are very likely to show some decomposition.

Many of the deposits dry out and mud crack during the times of drought. The edges of the polygons commonly turn up, but this feature may not be preserved, as wetting soon leads to wilting. In many instances the swamps and sloughs also dry up, and the fish and other animals die. A dried-out slough on the north side of the Kansas River, a few miles east of Lawrence, seen during the summer of 1914, had thousands of fish lying about on the surface of the partially dried muds. Many of these were no doubt eaten by animals and birds, but some could hardly have failed to become incorporated in the sediments. This destruction of organisms is not, however, confined to deposits of this type of climate, but may also occur under conditions of semiaridity, with certain differences noted in that connection which are unlikely under the conditions now being discussed.

In general, therefore, climates of the type considered are indicated in stream deposits by generally decomposed sediments, consisting mostly of shales and sands of blue and gray colors with occurrences of yellows and browns, the former more common, and locally of dark shales and thin coal beds. The shales and sands may contain some products that are not decomposed, and there may be micaceous sandstones if igneous or metamorphic rocks are adjacent; but decay generally will have advanced far enough to eliminate most of the original rock materials other than quartz and extremely resistant minerals, leaving residual products of quartz, clay, and iron and aluminum oxides and hydroxides. Soluble and colloidal products may be concentrated in or just below materials which remained at the surface for a time sufficiently long to permit concentration by capillary action. Some of the deposits of flood-plain swamps may contain many remains of fish and

[35] Barrell, J., op. cit., p. 270.

other river-dwelling animals, and these may be associated with thin coals and carbonaceous clays or shales. Mud-cracked clays and silts frequently have considerable development.

Marine sediments are not particularly likely to be affected directly by climatic conditions of the type considered, except that contributions from the land as a rule are increased because of the limited development of plant protection.

SEDIMENTS FROM REGIONS WITH SEMI-ARID CLIMATES

Regions with semi-arid climates do not receive sufficient moisture to support an adequate protective cover, and possess a more or less seasonal growth of animals and perennials, chiefly grasses and plants adapted to very dry conditions, as the yucca, some of the cacti, sage, prairie rose, some of the milkweeds, and many of the Leguminosæ. There are periods of seasonal rainfall, occasional rainfalls during the dry seasons, and the ground frequently becomes thoroughly soaked. There is a decided scarcity of arboreal vegetation, except along the stream courses, whose positions in the region may readily be located by its presence.

The thinness of vegetation renders the soil and rock accessible to attack by the occasional downpour, and there is a more or less flashy response to rainfall on the part of the generally intermittent streams; bad lands are extensive, and dry coulées of one hour may become filled with torrents of muddy water the next. Mud flow may be responsible for considerable transportation about bordering highlands. Sediments are rarely carried entirely out of semi-arid regions, but are left over such previously aggraded surfaces as flood plains and fans, the water disappearing through evaporation and absorption by the substratum. Few streams persist throughout the dry seasons.

Regions with semi-arid climates frequently have strong winds, and these, due to the scarcity of vegetation, may erode depressions to considerable depths. The occasional rains may change the depressions to ponds which, if sufficiently persistent, may contain an abundance of tadpoles and become the watering places of the region's animals. If the waters evaporate before tadpole metamorphosis is completed, the tadpoles are killed and become mummified on the mud-cracked surfaces. Such a pond on top of one of the foothills of the Big Horn Mountains in southern Montana showed, in July, 1921, mud-cracked silts over an area of about half an acre, each mud-crack polygon having stuck on its surface one or more tadpole mummies or skeletons. Some of the muds of these depressions are black from contained organic matter.

The soils and sediments of semi-arid regions are unleached and deficient

in humus. Hilgard[36] states they are relatively rich in nitrogen. The iron is likely to be either in the form of hydroxide, or unchanged in the minerals of the parent rock; it does not seem to be common in the form of carbonate. The tendency is for soluble materials, as soda, potash, lime, and magnesia, to be concentrated in the surface materials, particularly in depressions and over flat areas, where they remain because of the inadequacy of the rainfall to wash them out. Lime appears to occur to a considerable extent as sulphate, perhaps due to deficiency of decay of organic matter with consequent small production of carbon dioxide.[37] Waters are more or less constantly rising to the surface by capillary action and depositing their dissolved contents there, forming "hard pan," caliche, tepetate, kankar (kunkar), concretions, and cement for the surface materials. These deposits are in some areas so extensive that they form a "bed" up to several feet thick which has the undulations and irregularities of the topography. The surface may be made white by this deposition, and because of the abundance of sulphate the iron may be changed to that form. Pebbles and larger rock particles on the surface are frequently surfaced with desert varnish, seemingly a result of capillary action which brings dissolved matter to the surface and precipitates it there. The subsoils of semi-arid regions are not generally as distinct from the surface soils as is the case in more humid regions.

The nature of sediments deposited in semi-arid or immediately adjacent regions after short separation from parent rocks depends very largely upon the characters of these parents. Sediments derived from crystalline rocks are arkoses, or similar aggregates, and in nearly every case the minerals and rock particles and the sediments show the rocks of derivation.

Sediments deposited in semi-arid regions may bake for weeks and months on dry flood plains, alluvial fans, and mud flats, with thorough mud cracking and some rain pitting as consequences. Colors range from light to red, light brown, yellow, and gray seeming to dominate. They tend to be rich in dissolved matter, and occasional wetting may lead to segregation of the lime into concretionary masses. These tend to lie along certain horizons and many are hollow, and others have cracked or "bread-crust" surfaces. Such are some of the kankar.

The lime and other salts and colloidal matter in the silts and clays may cement the latter so firmly that the curled-up edges of the mud-cracked polygons are able to maintain their positions for some time after wetting, and the next water-laid deposit may fill the cracks and the spaces beneath. This may also be done by wind deposition in periods between rains. Salt and gypsum may occur locally, but the quantities are small unless the

[36] Hilgard, E. W., Soils, chapters 20 and 21.

[37] Clarke, F. W.. Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 93.

semi-arid region occurs adjacent to the sea, under which conditions there might be considerable concentration in lagoons.

Sediments accumulated under semi-arid climatic conditions seem to be rather common in the geologic column. Of this origin appear to be the Sparagmite sandstone of Sweden, the Torridonian sandstone of Scotland, the Old Red sandstone of Great Britain, the Connecticut Valley Newark series, the Mauch Chunk shales[38] of the Appalachian region, and some of the Permian Red beds of Kansas and Oklahoma.

SEDIMENTS FROM REGIONS WITH ARID CLIMATES

Arid climates seldom have rain; the ground is dry most of the time; vegetation is extremely sparse and of peculiar types, as cacti, euphorbias, etc. The widely separated rains are apt to be cloudbursts, and the disappearance of the water is a matter of a few days or a week, the sediments being carried short distances and dropped as the water percolates into the dry substratum. The following is a description of a cloudburst and flood in the desert of Atacama, north Chili:[39]

> On the 13th of July, 1880, there passed over Northern Chili a storm of wind and rain such as the oldest inhabitant had never seen. A little to the east of Yerba Buena—the terminus of the Carrizal and Cerro Blanco line—the rain fell in torrents and formed a river in each of the three small valleys that converge just above the station. [A head of water filled] the large valley, and the stones it bore along rattled and rumbled so loudly that the people about the station could hardly hear one another speak.

The flood wiped out 9 miles of railroad, but, so far as known, none of the water reached the sea.

Much of an arid region is bare surface of rocks and rock fragments; parts may be mountainous, and other parts are covered with fragments due to rock breaking, the winds in each case having removed most, or all, of the fine materials. Extensive areas are covered with sands, and some arid regions have silt-covered areas of considerable extent. Temporary lakes may be formed by each rainfall; their drying up makes the silty parts of deserts, and there may be more or less permanent salt or bitter lakes. The lakes may be at any elevation in wind-scoured depressions, and as these may contain waters only at long intervals, the designation of "dry lakes" is in keeping.[40]

[38] Barrell, J., Origin and significance of the Mauch Chunk shales, Bull. Geol. Soc. Am., vol. 18, 1907, pp. 449–476.

[39] King, T., Notes on a recent flood in the desert of Atacama, North Chili, Trans. Geol. Soc. Glasgow, vol. 7, pt. ii, 1885, pp. 262–263.

[40] Jutson, J. T., On the occurrence and interpretation of rock-cliffs and rock-floors on the western shores of the "Dry Lakes" in south-central Western Australia, Geol. Mag., vol. 55, 1918, pp. 305–313.

The general conception is that the rock particles of deserts result from rock disintegration in some form and that decomposition is not important. Blackwelder, however, states that diastrophism is responsible for a "copious supply of angular fragments" and that chemical changes produce "vast quantities of scales, rubble and sand," and that these two processes are largely responsible for the production of the materials found in the deserts of western North America.[41] It seems probable that the contributions from the different processes vary with the localities, the native rocks, and the conditions. It is obvious that diastrophism would not be important where rocks had been little affected thereby.

The sparseness of vegetation results in there being little organic matter in the soil. Surface materials may be high locally in lime, sodium, and other

TABLE 18

	A*	B*
Insoluble in HCl	84.031	70.565
Soluble SiO_2	4.212	7.266
Al_2O_3	4.296	7.888
Fe_2O_3	3.131	5.752
Mn_3O_4	0.133	0.059
MgO	0.225	1.411
CaO	0.108	1.362
Na_2O	0.091	0.264
K_2O	0.216	0.729
P_2O_5	0.113	0.117
SO_3	0.052	0.041
Water and organic matter	3.644	4.945

*A = average of 466 humid soils of the United States; B = average of 313 soils from the arid regions of California, Washington, and Montana. Hilgard, E. W., Soils, 1906, p. 30. Some of the "arid" soils may have been derived from semi-arid regions.

carbonates; lime and other sulphates; sodium chloride; etc. There are great differences in this respect. The chemical compositions of the soils of arid and humid regions are shown in table 18.

Capillary action may bring moisture with dissolved salts, leading to precipitation of salts, and thus to formation of caliche, kankar, and similar deposits. Caliche may be so abundant locally as to make the surface white. These salts to some extent serve as cement for the surface materials, and thus retard wind erosion, but some of them are very powdery and of little effect as cements, and are blown away about as rapidly as formed. The fine materials are sands, silts, and clays, the last commonly considered to

[41] Blackwelder, E., Desert weathering, Bull. Geol. Soc. Am., vol. 38, 1917, pp. 127–128.

be not common because of immature decomposition and because of easy removal by winds.

Desert materials tend to have light colors, or the colors of the rocks of derivation, thus gray, buff, yellow and light brown colors dominate.

The small particles loosed from parent rocks are swept about by winds. The fine materials, as produced, may be lifted into the higher parts of the atmosphere, carried out of the desert, and deposited in adjacent, more humid regions. Elevated parts of deserts tend to be more rapidly eroded, as they receive the full force of winds. The occasional rains wash the high places and carry all material within the range of competency of the resulting flow-off to depressions, whence the fine materials are removed by the winds. Over the low places the deposits protect the underlying bed rock from ablation. Ultimately the high places are reduced, those easiest of destruction lowering most rapidly. When places are sufficiently low, rock waste accumulates over them, sediments are directed to them, and erosion is checked. Ultimately the surface is reduced to a plain covered with lag gravels, the finer materials have been transported away to other environments, and the desert cycle is complete.[42]

The deposits made in regions of desert climates are due to both water and wind. The wind deposits have the cross-lamination, rounding, sorting, frosting, and facetted pebbles characteristic of deposits so made. The water deposits are the results of sheet-flood and torrential action at one extreme and of the quiet waters of ephemeral and more or less persistent lakes at the other. The wind deposits may be at any elevation, but those of water lie over the lowest parts of the desert. The deposits of the more or less ephemeral lakes are silts with little true clay. The silts usually contain a high percentage of lime, of which much is in the form of the sulphate, and they may be impregnated with sodium chloride and other salts. The carbonate of lime may become segregated to form concretions, and the sulphate and sodium chloride may aggregate to form large crystals. Interbedded with the silts may be sandstones which are micaceous, if crystallines are being eroded, and these also contain much feldspar. However, the abundant presence of feldspar and mica must not be considered as proving an arid climate, as both are deposited in other environments.[43] These mechanical deposits may contain layers of calcium carbonate, gypsum, and salt; and the evaporation products may be of greater thickness than those

[42] Davis, W. M., The geographical cycle in an arid climate, Jour. Geol., vol. 13, 1905, pp. 381–407; Passarge, S., Über Rumpfflächen und Inselberge, Zeits. d. deut. geol. Gesell., vol. 56, 1904, pp. 193–209.

[43] Reed, R. D., The occurrence of feldspar in California sandstones, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 1023–1024.

of mechanical deposition. Tracks of animals and their mummified bodies or skeletons may occasionally be found in the lake muds, but they do not seem to be common. Thus, Huntington[44] found the remains of a plover in the salt deposits of the Salt Plain of Lop in eastern Turkestan, but outside of a few roots of reeds, no other signs of life were observed in a journey of about 100 miles. Sourceward from the temporary lakes or depressions, the sediments first become sandy and, near the source, conglomeratic, with angularity of particles increasing. The colors of the ephemeral lake deposits are as a rule grays and white, but there may be local occurrences of reds, yellows, and blacks.

When the lakes dry up, the deposits become mud-cracked, the prolonged drying causing the edges of the mud-crack polygons to turn up and form concave upper surfaces. Before the next rain the cracks and the spaces beneath the polygons may become filled with wind-deposited sand and silt, and wind deposits may cover the whole. The gypsum, sodium chloride, and layers and crusts of other salts may crack and buckle, and the surface of the deposits become ridged with wave-like surfaces as described by Huntington for Lop Nor in Persia. Thin mud-crack polygons may be broken up by winds to form small angular and coin-shaped plates whose burial may give rise to a desiccation breccia.

Summarizing, arid climates yield sediments which result from both rock breaking and rock decomposition; there is little or no carbonaceous matter; colors are wont to be light, but occasional red, yellow, and dark colors may be present. Salt, gypsum, and lime deposits of considerable thickness are probable, and there may be occasional tracks of animals and rarely some of their remains. The various types of deposits dovetail into each other.

CLIMATE AND MARINE SEDIMENTS

Marine sediments do not indicate climate as plainly as do continental. The physical characters of the sediments mean little, and the type of minerals gives no light, as they may have been eroded from the shores. The colors usually are changed from those of deposition by reason of the reduction produced by the organic matter commonly present. Dunes are common on beaches, and their sand grains must enter into marine sandstones. Glacier-borne materials brought to the sea may escape the wash of waves and thus give evidence of a cold climate on the lands near the sites of deposition, and large blocks in marine clays and shales suggest icebergs and rigorous climate somewhere during the times of deposition. Organisms buried in marine sediments are more valuable for their bearing on climate than any other characteristics, but it should never be forgotten that the animals of the past

[44] Huntington, E., The pulse of Asia, 1907, pp. 252–253.

may not have lived under the same climatic conditions as do their relatives of the present.

Modern reef corals, and presumably those of past geologic periods, require temperatures which do not fall below 68°F., and the occurrence of such forms in various parts of the geologic column is considered evidence that the waters of deposition were not colder than those in which their modern descendants live. On this basis it is assumed that the Ordovician and Silurian coral reefs of the Baltic and northern seas were formed in waters of tropical climate, but it is by no means certain that the assumption represents fact.

The bottoms of the warm modern seas do not seem to possess a much greater development of benthonic life than do those of the moderately cold seas, but the number of species in the former is said to be greater than in the latter, and shells of warm waters seem to be generally heavier than those of cold, although there are many exceptions. The uniformly warm temperature of tropical seas leads to a greater precipitation of lime carbonate by benthonic and planktonic lime-secreting organisms than is the case in colder waters, in which shell forming is inhibited during the colder months.[45] The deposits of the pelagic organisms are largely responsible for the calcareous oozes which have greater development in tropical than in colder seas.[46] It is also probable that precipitation of lime carbonate through escape of carbon dioxide and production of ammonia is greater in warm than in colder waters. This results in greater thickness of limestone accumulations in tropical than in polar and polar-temperate regions, and great limestone formations are considered evidence of warm climates over the places of occurrence during the times of deposition.

SEDIMENTS RESULTING FROM CLIMATIC CHANGE

Climatic change is expressed in differences in erosion at the headwaters of the streams, differences in capacity and competency of transportation and changes in methods of transportation,[47] and differences in rates of deposition and thickness of deposits. Climatic change, so far as sediments are concerned, may be comprehended in changes in rainfall and changes in temperature.

Sediments Resulting from Changes in Rainfall

Change of climate from semi-arid to rainy will cause streams to remove sediments previously deposited. Under semi-arid conditions the deposits are made on flood plains and alluvial fans. After change to more humid

[45] Murray, J., and Irvine, R., On coral reefs, etc., Proc. Roy. Soc. Edinburgh, vol. 17, 1889–1890, pp. 79–109 (81–82).

[46] Murray, J., and Irvine, R., op. cit., pp. 81–82.

[47] Barrell, J., Jour. Geol., vol. 16, 1908, pp. 370–381.

conditions, these deposits start downstream toward the deltas. Changes are probable in three places: the headward parts of the streams have increased erosive power; the piedmonts become the sites of erosion; and the deltas receive a large influx of sediments which are somewhat finer than when they were a part of the piedmont deposits. The deltas may build outward. Prior to climatic change the deltas were receiving sediments which, because of limited competency of the streams, were fine materials, and the quantity was small because of limited capacity. Concomitant with climatic change the streams became larger and swifter, giving greater capacity and competency, with increase in load due to easy erosion of the piedmont materials. The deltas thus receive a large addition of much coarser material than previously. With removal of the piedmont deposits, there is greater difficulty in obtaining a load; and tending toward the same end is growth of vegetation, which, by the time the piedmont deposits have been removed, will have attained effectiveness as a cover. There will also be a lowering of stream gradients, with the consequence that fine deposits will succeed coarse, the latter being the immediate results of climatic change. These fine deposits are apt to be thin.

Climatic change from wet to dry will decrease the effectiveness of the vegetable cover and the capacities and competencies of streams in the region of the piedmonts and downstream therefrom. Materials brought from head waters have their coarser constituents left on the piedmonts; finer deposits pass onward to be deposited farther downstream on the deltas and in the sea. There is a decrease in quantity and coarseness of sediments deposited on deltas and about the mouths of streams. Delta fronts may recede. Piedmonts receive deposits of sands and coarser materials, and deltas, deposits of sands, silts, and clays.

The above types of climatic change in the first case yield coarse deposits to piedmonts and fine to deltas, and thus "gravel deposits on the piedmont slopes" may have a climatic significance "precisely opposite in character to the same when found on the delta plain."[48] But these inferences relating to climate cannot safely be made until it has first been shown that the sediments are not related to diastrophic causes, and only after there has been a correlation of events for the three portions of a river: its source, piedmont, and delta.

Sediments Resulting from Changes in Temperature

Climatic change from rigorously cold to cool without increase in precipitation will probably decrease the quantity of sediments and change

[48] Barrell, J., op. cit., pp. 380–381.

their character rather markedly. Under the former conditions sediments are largely of physical origin, whereas the change to warmer conditions may lead to the development of a plant cover and correlative effects. Decomposition becomes important, and clays, silts, and quartz sands result. Light colors give place to darker from incorporation of organic matter.

Climatic change from cool to warm without increase in precipitation may decrease the effectiveness of the plant cover because of increased evaporation, and the change would be expressed over the sites of deposition influenced by the regions of change by increase in coarseness, rate of deposition, and quantity of sediments.

Effects of temperature-change can probably best be illustrated through consideration of two regions: northeast central Texas and Anticosti Island. The former has a climate which does not favor the development of an effective plant cover, whereas Anticosti is clothed nearly everywhere with a heavy mantle of living and dead vegetable matter. The rainfall in each case is approximately the same. In Texas the streams almost always have some degree of turbidity and are excessively muddy during high water; the streams of Anticosti seem to be clear at all times. The sites of deposition of the streams originating in or flowing through north central Texas are receiving large volumes of mud, whereas the Anticosti streams are carrying essentially no suspended matter to the sea. Could Anticosti Island have its temperature conditions changed to those of northeast central Texas, rainfall remaining the same, the vegetable cover would be eliminated, and the change would be expressed in the deposits of the adjacent sea bottom by muds rich in peaty materials and limestone gravels and sands of great thickness. On the other hand, could northeast central Texas be given the temperature conditions of Anticosti, precipitation remaining unchanged, vegetation would quickly mantle the surface, transportation of inorganic matter by the draining streams would largely cease, and the sites of deposition would receive only fine terrigenous and pelagic sediments. In the Anticosti region the change from a low to a high temperature would produce a thick clay, sand, and gravel deposit, and in northeast central Texas a change from high to low temperature would lead to limestones succeeding muds, giving in each case a sequence which ordinarily is interpreted as due to topography.

Sediments in Relation to Migration of Shorelines

A shoreline may migrate either landward or seaward. Landward migration may be accomplished by rise of sea level or by inland erosion with stationary sea level. The results from the point of view of the sediments are quite different. Seaward migration may take place with stationary sea level through building outward of the shore, or because of fall of sea level.

Migration of shoreline changes the distance from the shore of any given place on the bottom, and the depth of water at the place. As a consequence of these changes, succeeding sediments of the place are different. The three factors of distance from the shore, depth of water, and character of the bottom largely control the nature of the benthonic fauna.

An invading shoreline consequent to a rise of sea level produces deeper water; the character and quantity of clastic material are changed; and somewhere adjacent to the new shore relatively rapid accumulation of sediment occurs, due to the fact that the slopes of much-submerged land are steeper than the profile of equilibrium determined by the conditions, making necessary a considerable deposit to adjust the slopes. This material in large part is derived from the coast, which is open to wave attack because of relatively deep water near shore. The invading waters also are likely to find much residual material on the invaded land, and this material is easily moved. Thus, at any place there may be deposited a thin layer of sediments derived from residual soil, and these will be succeeded by coarser sediments composed of particles derived from erosion of bed rock. With further advance of shoreline, these first-deposited sediments become overlain by those of deeper waters, which are finer than the preceding and also in thinner beds. Hence, under conditions of an invading sea consequent to rise of sea level, the sediments in any section may grade upward from materials of a certain degree of fineness to others which are coarser, and these in turn should grade upward into finer sediments. The sequence rests on a surface which in places is due to shore erosion, each layer overlapping the preceding in the direction of the shore, and each facies migrating transversely upward in the section. The extent of the shore-eroded surface is related to the rapidity of rise of sea level, being best developed under conditions of slow rise. Each sedimentary unit should therefore become coarser shoreward, with considerable variation of the shoreward materials both in dimension and thickness.

An invading shoreline with stationary sea level develops an eroded bottom surface coextensive with the area of invasion. No permanent deposits are made on this surface so long as sea level remains unchanged. Materials torn from the rocks of the coast remain with the beach or in shallow water until reduced to particles sufficiently small to be transported across the wave-cut surface to deeper waters below the profile of equilibrium. The sequence should contain few or no coarse deposits.

A retreating sea consequent to a lowering of sea level moves outward over an established profile, but one that is established for a greater depth of water than exists after the retreat. In the shallower waters near the new shore the former profile may be too flat for the conditions, and rapid erosion of

the bottom is a consequence. The sediments subject to removal are carried to deeper waters to form deposits which are likely to be coarser than those upon which they rest, and the rate of deposition becomes more rapid than was the case before the retreat occurred. The new profile of equilibrium is cut across the deposits of the earlier position of the sea and likewise some of those which were made immediately following the retreat. Temporary deposition may occur on bottoms above the profile of equilibrium for the conditions, such as barrier islands and associated deposits, but ultimately these are removed. Thus, a part of the record locally is lost, and there is an outlap of later deposits with respect to earlier. Retreat of sea through fall of sea level is indicated by sediments of a certain degree of fineness and rate of deposition, overlain by coarser sediments of a more rapid rate of deposition.

If sea level falls at a rate slow enough to prevent the formation of barrier islands, and the retreat of the shore is not intermittent and not balanced by inland erosion, a sheet of gravels is left over the abandoned bottom. Intermittent retreat leaves successive thick bands of beach materials, each band marking a former sea level.

Retreat of a shoreline may also be produced by prograding, the deposits of which are certain to be ultimately removed if the static condition to which the prograding is due is not interrupted. If there is interruption through rise of sea level, some of the deposits of the prograding may be preserved.

A great deal has been said relative to conglomerates made by an advancing sea, and the general conception of a marine sequence pictures a basal conglomerate as its initial deposit; it has been stated, however, that in those "cases where a rapid transgression of the sea took place, or where fine, residual soil on the old surface is but slightly reworked, such basal rudytes may be wanting."[49] How rapidly a shore may advance can only be surmised; it is probable, however, that no advance has been so rapid as to prevent all ordinary residual materials of average thickness, excepting very locally, from being worked over and the large fragments ground to pieces. As has been stated above, basal conglomerates are possible under the conditions of an advancing sea due to rise of sea level over those portions where the profile of equilibrium is above the new bottom, and are not probable under other conditions. As basal conglomerates appear to be rather rare at the bases of marine sequences, it therefore appears that the inland migration of most shores must have been very slow instead of rapid.

Sediments and Fire

This chapter would not be complete without a consideration of the effects of forest and prairie fires on deposition of sediments. Such fires

[49] Grabau, A. W., Principles of stratigraphy, 1913, p. 833.

probably have occurred since the beginning of land vegetation. They are extremely prevalent at the present time, and many hundreds of square miles are burned over each year. It is the opinion of Högborn[50] that forest fires probably covered larger areas before the advent of man than now, not because more were started, but because their extinguishing was due entirely to natural causes, whereas at present many fires are extinguished by human agencies. Attention has already been directed to the effectiveness of fire in rock breaking,[51] and there is little doubt that this agent is of great geological importance, but little has been said relative to the effects of fire upon the character and quantity of sediments ultimately deposited.

A great forest or prairie fire deprives the surface materials of protection and thus makes them extremely vulnerable to attack by the agents of removal. On level or nearly level surfaces and over swamps a fire ordinarily may do little harm, but on surfaces of considerable relief the results may be extremely great. Even swamp fires may burn the dead and accumulated plant materials to great depths, as the well known peat fires demonstrate. A fire over a mountain area may not only burn off the standing plant life, but may destroy the accumulations of years and leave bare slopes from which the agents of erosion rapidly move away the soils and later the broken rocks beneath them. The results will be expressed over the sites of deposition in fine materials derived from the residual soils, these resting on deposits made when mountain slopes were forest-covered, and succeeded by sediments of coarser character derived from surfaces denuded of their residual soils. Charcoal from the fire might, but would not necessarily be present, because its specific gravity would lead to its being floated and thus widely scattered. Ultimately plant growth would recover the surface and the sediments would return to their original characters. The coarse materials would indicate nothing of diastrophism, no change of level, and no climatic change. How many deposits of the geologic column contain sediments which owe some of their characters to fire cannot be stated, but is it extremely probable that that there are many.

[50] Högborn, I., On the geological importance of forest fires, Bull. Geol. Inst. Upsala, vol. 15, 1916, pp. 117–124.

[51] Blackwelder, E., Fire as an agent of rock weathering, Jour. Geol., vol. 35, 1927, pp. 134–140.

CHAPTER IV

SEDIMENTS AND ORGANISMS

The subject has two aspects: the modification of sediments by organisms, and the influence of the sediments and the conditions responsible for their characteristics on the organisms which live upon them. Environmental factors determine the types of organisms which may be present, and important factors in this environment are the sediments and sedimentary conditions which are responsible for the substratum. A given environment provides the optimum of conditions for certain organisms, prevents the entrance of others, and permits certain forms to exist with greater or less difficulty.

There need to be differentiated the environment of life, the environment of death, the environment of the body after death, and the environment of burial. As Wasmund[1] has noted, the paleobiologic and paleogeographic result, the reconstruction of the former life relationships, can only be attained when the environments of both life and death are known. To the collectivity of life relationships the term of *Biocœnose* has been applied, and Wasmund has proposed the designation of *Thanatocœnose* for the death associations and relationships. In life an organism is limited to a certain environment, from which it does not widely depart. In death the preservable parts are no longer under the control of the factors of life environments, but under those which control materials of inorganic origin, and thus may enter environments which the living organisms could not have endured. In life, for example, the common Gulf of St. Lawrence echinoderm, *Strongylocentrotus dröbachiensis*, and the common black mussel, *Mytilus edulis*, require certain shallow-water ecologic factors for their existence. In death the shells are found in shallow and deep waters and on beaches, and as crows and gulls use the animals for food, the shells are carried inland, where they may be found in streams, on moors and in swamps, and in the forest. The environments of life, death, after death, and burial are different. The ancient graptolites, which in many cases seem to have been a part of the plankton, are best and most abundantly preserved in black shales, yet it seems obvious that they did not live in any greater degree of abundance in

[1] Wasmund, E., Biocœnose und Thanatocœnose, Archiv für Hydrobiologie, Bd. 17, 1926, pp. 11–116; Twenhofel, W. H., Environment in sedimentation and stratigraphy, Bull. Geol. Soc. Am., vol. 42, 1931, pp. 407–424.

the waters overlying the black muds than in waters over whose bottoms other sediments were being deposited. It may be that their entrance into the waters over whose bottoms the black muds were being deposited was the cause of death. The environment of the bottom may have been the cause of their attaining burial, and burial in fine black muds may have been the cause of their preservation. Thus, the conditions of four environments require consideration.

Modification of Sediments by Organisms

There are two phases of the modification, that resulting from the passage of sediments through the intestinal tracts of organisms, and that brought about through the boring of organisms into organic or other structures which exist on or about the places where they live.

As pointed out by Darwin,[2] some tracts of land have 50,000 or more earthworms to the acre, and he estimated that these transport 18 tons of earth per acre to the surface annually. As all of this earth has been subjected to the action of the intestinal juices, it is certain that it has experienced both physical and chemical change.

The lob worms on some of the sand flats exposed at low tide between the coast of Northumberland and the adjacent coast of Holy Island eat the sands through which they burrow and bring their excreta to the surface in the same way as earthworms. Davidson[3] estimates that the individual castings average 84,423 per acre at any one time, or around 50,000,000 per square mile. At the places of maximum occurrence of the worms, it is estimated that 3,147 tons per acre annually pass through their intestinal tracts and are brought to the surface, and that there is an average of 1,911 tons per acre. The worms are estimated to burrow to a depth of 2 feet, and this thickness at the places of maximum occurrence may pass through the intestinal tracts in about 22 months. Under conditions of slow deposition it follows that the bottom materials are eaten many times. The qualitative effects of passage through the intestinal tracts are not known. Walther[4] states that in Rothesay Bay, Scotland, where the shore is made of sand and mud, it serves as the home of worms which eat the mud in which they dwell, and he concluded that the sediments of the bay are in continuous passage through their intestinal tracts. The extent to which some of the marine worms gorge themselves with sands is shown by the fact that the average weight of *Sipunculus nudus* from the Bay of Naples was found to be 19.08

[2] Darwin, Chas., The formation of vegetable mould, 1883.

[3] Davidson, C., Work done by lob worms, Geol. Mag., vol. 28, 1891, pp. 489–493.

[4] Walther, J., Einleitung in die Geologie, 1894, pp. 102–103.

grams, of which the sand washed from the alimentary canal constituted 10.03 grams.[5] Murray and Lee[6] state that the continental shelf

constitutes the great feeding ground of the ocean. Large numbers of Holothurians and other marine creatures eat the mud to obtain the organic matter associated with it; indeed, it is more than probable that all marine deposits are in this way passed through the intestines of organisms. Very many crustaceans frequent this area to pick up little particles of organic matter which are just settling on the bottom, and some of them—like *Nyctiphanes*—are provided with phosphorescent organs to do this more effectively.

Verrill,[7] describing the bottom beneath the Gulf Stream off the coast of New England, states that there is an abundance of entire and broken shells, and that

Many fishes, like the cod, haddock, hake, etc., have the habit of swallowing shells entire and after digesting the contents, they disgorge the uninjured shells, and such fishes abound here. The broken shells have probably been preyed upon by the crabs and other crustaceans, having claws strong enough to crack the shells. The large species of *Cancer* and *Geryon*, and the large Paguroids, abundant in this region, have strength sufficient to break most of the bivalve shells. Although I have often seen such crustacea break open bivalves for food, I am well aware that they feed on other things. Many fishes that feed on Mollusca break the shells before swallowing them so that both fishes and crabs have doubtless helped to accumulate the broken shells that are very often scattered abundantly over the bottom, both in deep and shallow water. Such accumulations of shells would soon become far more extensive if they were not attacked by boring sponges and annelids. Certain common sponges belonging to the genus *Cliona* very rapidly perforate the hardest shells, in every direction, making irregular galleries and finally utterly destroying them. In our shallower waters the most destructive species is *C. sulphurea* (Desor), which burrows in shells and limestone when young, but later grows into large, rounded, sulphur-yellow masses, often a foot in diameter. Rarely, we dredge up, on the outer grounds, fragments of wood, but these are generally perforated by the borings of bivalves (usually *Xylophaga dorsalis*) and other creatures, and are evidently thus soon destroyed. Very rarely do we meet with the bones of vertebrates at a distance from the coast. Although these waters swarm with vast schools of fishes, while sharks, and a large sea porpoise or dolphin (*Delphinus*, sp.) occur in large numbers, we have, very rarely indeed, dredged up any of their bones, or, in fact, remains of any other vertebrate animals. In a few instances, we have dredged a single example of a shark's tooth, and occasionally the hard otoliths of fishes. It is certain that not merely the flesh, but most of the bones, also, of all vertebrates, that die in this region are very speedily devoured by the various animals that inhabit the bottom.

About coral reefs are found fishes which browse upon the corals and algæ, and it is probable that the crinoid patches served similarly for some animals

[5] Shipley, A. E., in Worms, etc., Cambridge Nat. Hist., Macmillan Co., 1894, p. 423.

[6] Murray, J., and Lee, G. V., The depth and marine deposits of the Pacific Ocean, Mem. 38, Mus. Comp. Zool., 1909, pp. 160–161.

[7] Verrill, A. E., Am. Jour. Sci., vol. 24, 1882, pp. 449–450.

of the past. Darwin[8] opened several of these fish and found their intestines filled with small pieces of coral and finely divided calcareous matter. Crustacea are among the most voracious of the animals inhabiting the sea bottom. They eat everything: flesh, mud, shells, sand, etc., and the material after passage through the intestinal tracts is finer than when it entered, and some of the lime mud of the sea bottom may be due to crustacean work.[9] Echinoids eat vast quantities of sand for the contained organic matter, and the grinding of these sands in the intestinal tracts must reduce them to smaller dimensions,[10] and in addition they may undergo some solution. According to Scott,[11] the chief food of the sea urchin is seaweed and sand, and Verrill[12] has stated that the grinding up of the shells about the Bermudas was accomplished in the intestines of a large species of sea urchin (*Toxopneustea*) and two species of holothurians, individuals of each species having been found with their intestines filled with sand. According to Yonge[13] the thick tentacles about the mouths of holothurians "continuously shovel sand and anything it may contain into the mouth, whence it passes through the entire alimentary canal of the animal." Sea urchins live in great numbers over certain parts of the sea bottom and, where abundant, they form a thick carpet. Certain bays on the coasts of Mingan Islands and Anticosti have sea urchins in almost countless numbers, and everything on the sea bottom in these bays must have made many trips through their intestinal tracts. Petersen[14] and Blegvad[15] have shown that the oyster and other mollusks and worms "literally stuff themselves" with the upper layer of fine detritus "which mantles some portions of the sea bottom about the Danish coast," and Jensen[16] has presented evidence suggesting that the passage of this matter through the intestinal tracts tends to increase the nitrogen content.

Many animals drill holes into solid materials. Such are some bacteria,

[8] Darwin, C., Structures and distribution of coral reefs, 3rd ed., 1880.

[9] Grabau, A. W., Principles of stratigraphy, 1913, p. 415.

[10] Kindle, E. M., A neglected factor in the rounding of sand grains, Am. Jour. Sci., vol. 47, 1919, pp. 431–434.

[11] Scott, F. M., Food of the sea urchin, Contrib. to Canadian Biol., vol. 5, 1901, pp. 50–52.

[12] Verrill, A. E., Notes on the geology of the Bermudas, Am. Jour. Sci., vol. 9, 1900, p. 330.

[13] Yonge, C. M., A year on the Great Barrier Reef, 1930, pp. 75–78.

[14] Petersen, C. G. J., The sea bottom and its production of fish food, Rept. 25, Danish Biol. Station, 1918, p. 9.

[15] Blegvad, H., Food and the conditions of nourishment among the communities of invertebrate animals found on or in the sea bottom in Danish waters, Rept. 22, Danish Biol. Station, 1914, pp. 41–48.

[16] Jensen, P. B., Studies concerning the organic matter of the sea bottom, Rept. 22, Danish Biol. Station, 1914, pp. 22–24.

many algæ, numerous worms, gastropods, barnacles, pelecypods, echinoids, sponges. Barrows[17] and Jehu[18] have assembled some of the data relating to these forms. About Funafuti one of the *Gephyrea* simply riddles the *Lithothamnium* deposits, and were it not for the great recuperative ability of this alga, its structures would be reduced to mere skeletons.[19] Worms bore through shells and rocks, and certain sponges, like *Cliona*, drill holes in shells. Similar work is done by some of the gastropods, and many of the algæ are noted for their work in this respect. There are several pelecypods which are famous for destructive work, and forms like the "shipworm" are a menace to human constructions. Some of them drill holes in extremely hard limestones and other rocks, and sea urchins do a like work on certain coasts.

Wherever bottom conditions are favorable to organisms which eat mud and bore into shells and rock, everything is likely to be reduced ultimately to powder, and there is little chance for shells and tests of organisms to be preserved. As scavengers and borers have wide distribution, such effects should have distribution nearly coextensive with shallow-water bottoms. Only where conditions of deposition or growth of organic matter are extremely rapid, where bottoms are unfavorable for scavengers and borers, or where "epidemics" lead to accumulation of organic matter beyond the capacity of scavenger disposition,[20] does it seem possible for well preserved organic remains to persist to permanent burial. This generalization merits careful consideration in interpretation of the fossiliferous portions of the geologic column. The portions with comminuted organic matter, unless it can be shown that the comminution is due to wave and current action, should be interpreted as having been deposited where scavengers and borers were abundant. This has been given even further application by Buchanan,[21] who states that "the principal agent in the comminution of the mineral matter found at the bottom of both the deep and shallow seas and oceans is the ground fauna of the sea, which depends for its subsistence on the organic matter which it can extract from the mud." The "same causes are at work in deep as in shallow seas," and "the matter forming the bottom of the sea is being continually passed and repassed through the bodies of

[17] Barrows, A. L., Geologic significance of fossil rock-boring animals, Bull. Geol. Soc. Am., vol. 28, 1907, pp. 965–972.

[18] Jehu, T. J., Rock-boring organisms as agents of erosion, Abstract, Geol. Mag., vol. 55, 1918, pp. 520–521.

[19] Grabau, A. W., Principles of stratigraphy, 1913, p. 415.

[20] Becking, L. B., Tolman, C. F., McMillin, H. C., Field, J., and Hashimoto, T., Diatom "epidemics" and an analysis of diatom oil, Econ. Geol., vol. 22, 1927, pp. 356–368.

[21] Buchanan, J. Y., On the occurrence of sulphur in marine muds and nodules, and its bearing on the mode of formation, Proc. Roy. Soc. Edinburgh, vol. 18, 1890–1891, pp. 17–39.

the numerous tribes of animals which demonstrably subsist on the mud and its contents." The excreta are mostly in the form of pellets, and these seem to be extremely abundant over many parts of the sea bottom. Vaughan states that the ellipsoidal bodies described by him in 1924 are castings of mud-feeding organisms and he also thinks that the ellipsoidal aggregates described by Thorp as composing a considerable part of the "coprolitic mud" are castings of mud-eating organisms.[22]

The organic materials deposited in swamps may be greatly modified by organisms before permanent burial. So long as these organic materials contain free oxygen, they are inhabited and eaten by various worms and bugs and thoroughly worked over by aërobic bacteria. After free oxygen is excluded or exhausted, anaërobic bacteria continue the work of destruction and modification.

There should be mentioned in this connection the gastroliths or stomach stones which were polished by muscular action in the digestive organs of some ancient reptiles, and which may still be found in the same organs of many modern birds, reptiles, and seals,[23] these being known as "ballast" in seals and penguins. Stomach stones occur locally in great number, and although they do not constitute a large percentage of the containing sediments, their occurrence introduces a peculiar component.

With several authorities considering that nearly all marine deposits pass through the intestinal tracts of organisms and that the major portions of marine deposits are excretions, and it being certain that such action is extensive, it follows that the modification of sediments by organisms has tremendous significance.

For the sake of completeness it is noted that the accumulated remains of organic matter, as shell limestones, coal, etc., are due to organisms, and the same is true of the carbon dioxide, hydrogen sulphide, ammonia, and other gases resulting from bacterial and other organic activity.

Influence of Sediments and Sedimentary Conditions upon Organisms[24]

To arrive at the origin of any sediment requires a reconstruction of the environment in which the sediment was deposited. The organisms found in sediments are important aids to this end, but before this assistance may

[22] Vaughan, T. W., Letter of August 24, 1931; Oceanography in its relation to other earth sciences, Jour. Washington Acad. Sci., vol. 14, 1924, pp. 307–333 (327, pl. 1); Thorp, R. M., Descriptions of deep-sea bottom samples from the western North Atlantic and the Caribbean Sea, Bull. Scripps Institution Oceanography, Tech. Ser., vol. 3, 1931, pp. 7–8.

[23] Murray, J., and Renard, A. F., Deep sea deposits, 1891, p. 321.

[24] The reader should consult "The fossil and its environment," Bather, F. A., Quart. Jour. Geol. Soc., vol. 84, 1928, pp. lxi-xcviii.

be utilized it is essential that the influence of sediments and sedimentary conditions upon organisms should be understood and appreciated.

It would seem unnecessary to emphasize the fact that organisms are adapted to environments, but a brief examination of stratigraphic literature readily serves to show the little consideration given to this generally accepted and very important fact. Correlation of a sedimentary unit is or is not made on the basis of the presence or absence of certain individuals or groups of individuals, or the percentage basis of the composition of the faunas is utilized. Where faunas are different, the question has rarely been raised respecting the possibility that the environments were such as to prevent the entrance of organisms into one environment which were abundant in another.

One of the most important factors of an environment is the nature of the substratum on which the sediments come to rest. This is progressively changing as the sediments accumulate, and locally shows extremely great variation both horizontally and vertically, thus changing both in space and time. That this now is the case is shown by many of the shallow-bottom studies which have been made, and it is well shown in many geologic sections. Herdman[25] stated that in the Irish Sea, "Probably the nature of the deposit is the most important of the various factors that determine the distribution of animals over the sea-bottom within one zoological area. It is certainly more important than mere depth; a muddy bottom will support a similar fauna at ten fathoms in one place and at fifty fathoms in another;" and Sumner[26] states that the character of the bottom considered chiefly in relation to its physical texture is "foremost among the conditions determining the distribution of the bottom-dwelling organisms," and this is admirably shown in his figures of distribution of many species. Walther's[27] work on the faunas of the Bay of Naples has shown the occurrence of a most striking illustration of the control upon organisms exercised by the character of the bottom. Rising from a muddy bottom ranging from 200 to 500 meters below sea level is the Tauben Bank, with its summit ranging from 45 meters below sea level to 50 meters above. In 1885 the submerged part of the bank was covered with calcareous sands upon which lived a

[25] Herdman, W. A., etc., The marine zoology of the Irish Sea, Rept. British Assoc. Adv. Sci., 1894, pp. 318-334 (330).

[26] Sumner, F. B., An intensive study of the fauna and flora of a restricted area of sea bottom, Bull. Bureau of Fisheries, vol. 28, 1908, see particularly figures 5, 27, and pl. 24; See also charts I-XIV of Allen, E. J., On the fauna and bottom-deposits near the thirty-fathom line from the Eddystone Grounds to Start Point, Jour. Marine Biol. Assoc. U. Kingd., vol. 5, 1897-1899.

[27] Walther, J., Die Sedimente der Taubenbank im Golfe von Neapel, Anhang z. d. k. Preuss. Akad. Wiss., Phys.-Math. Kl., Berlin, 1910, pp. 1-49.

luxurious development of plant and animal life, whereas the flora and fauna living on the deeper muddy bottom surrounding the Bank were composed of fewer individuals and fewer species. The top of the Bank was the home of 360 species of animals; 142 species lived on the mud bottom surrounding it. Counting only those animals possible of fossilization, there were 310 on the top of the Bank and 45 on the mud bottom; there were only 14 common species. These figures indicate that the faunal contrast was greater than the contrast in sediments.

Every student of modern land and shallow-water faunas and floras is aware that the distributions of many species are discontinuous, that many tracts have very little macroscopic life at all times, and that the life on a given tract varies from time to time both in kind and quantity. The Tauben Bank area was restudied by Walther in 1910, 25 years after his first study. He found that the bottom had become covered with lime-precipitating algæ, and that former benthonic forms had been largely expelled. Similarly, when forests of Wisconsin and adjacent states are burned over and their conifers killed, the succeeding growth consists largely of poplars, a floral change which may occur in a very short interval of time.

The "ship worm," *Teredo*, has extensive distribution along the Atlantic and other coasts, but there is considerable discontinuity in the distribution. *T. navalis* is absent or extremely rare from Halifax southward to the end of the peninsula, in the Bay of Fundy, and along the north quarter of the Maine coast. According to Kindle,[28] the destructive work of this pelecypod seems to be greatest where the bottoms are sandy. Studies made by H. F. Blum[29] have suggested that salinity is the factor responsible for the occurrence or absence of this shell, but as *T. navalis* appears to be able to endure a range from about 6 to 35 parts of salt per thousand, it does not seem that this factor is adequate to explain its discontinuous distribution on the Atlantic coast.

It is known that the dissolved contents of natural waters are factors in the modification or limitation of organisms. Thus, in the Baltic, Black, and Caspian seas, with their low salinity, many organisms of the open ocean do not occur, and the majority of those present are dwarfed to much smaller sizes than are normal for the species. High salinity and most other characters of water abnormal to environmental conditions of organisms also lead to dwarfing.[30]

According to McClendon,[31] there is an optimum hydrogen-ion[32] concen-

[28] Kindle, E. M., Biological contributions, Sessions Paper No. 38a, 1918, pp. 93–191.

[29] Blum, H. F., Science, vol. 57, 1923, p. 9.

[30] Shimer, H. W., Dwarf faunas, Am. Nat., vol. 42, 1908, pp. 472–490.

[31] McClendon, J. F., On the changes in the sea and their relations to organisms, Publ. 252, Carnegie Inst. of Washington, 1918, pp. 233–234.

[32] The unit of hydrogen-ion concentration is 1 n H, or about one gram of hydrogen ion

tration range for plants, which may be different for different species, although it has not been worked out for the entire life history of a single species. The photosynthesis of plants, and therefore their growths, vary directly with the CO_2 tension and illumination. Photosynthesis is more than doubled by a 10°C. rise in temperature, but this does not mean a greater plant growth in tropical regions, for as he states, "the number of grams of plant tissue per square meter of sea surface is less in warm seas than in cold seas," and some other limiting factor is responsible for the difference.

A more abundant growth of eel grass flourishes on the west side of Loggerhead Key of the Tortugas than on the east, perhaps because sewage and garbage contamination prevails on the west side, or possibly because the water on the west side is less agitated by wind. Abundant eel grass flourishes in the shallow water around Marquesas, which may be related to the abundant fixed nitrogen washed into the sea from the decaying organic matter of the shore. McClendon also suggests that the denitrifying bacteria described by Drew and others may be a limiting factor in the growth of plants, the bacteria depleting the water of its nitrogen salts and thus depriving plants of this source of food; and Drew[33] has assigned to this cause the "relative scarcity of plant life (and consequently of animal life) in tropical as compared to temperate seas." The scarcity of oxygen in such waters as the Black Sea, and the development of hydrogen sulphide, are important factors in limiting the occurrence of organisms, the shells of *Cardium edule* in black sands on the coast of the Wash on the east coast of England, for example, averaging only about half the size of those living in sands of other color.[34] The blackness was found by Bruce[35] to be due to the presence of ferrous sulphide, for whose formation hydrogen sulphide was probably responsible.

Food is a most important factor in the distribution of organisms. The cod of the North Atlantic follows the migrations of certain fish, and most fish migrate with their prey.

The depth and turbidity of water control the quantity of light received, and the latter controls the development of plant life and indirectly the quantity of animal life. It has been shown that marine algæ are adapted

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per liter. The concentration is usually expressed by the symbol P_H with a following number, this number representing the negative logarithm of the concentration, as pH1, the 1 indicating a hydrogen-ion concentration of 0.1 n H.

[33] Drew, G. H., On the precipitation of calcium carbonate in the sea by marine bacteria and on the action of denitrifying bacteria in tropical and temperate seas, Papers from the Tortugas Lab. of the Carnegie Inst. of Washington, vol. 5, 1914, p. 9.

[34] Kindle, E. M., The intertidal zone of the Wash, England, Rept. Comm. Sed. Nat. Research Council, 1930, p. 15.

[35] Bruce, R. J., Jour. Marine Biol. Assoc. U. Kingd., vol. 15, 1928, p. 565.

to different light intensities, a minority requiring strong light intensity and the majority being adapted to light of less intensity.[36] In Lake Ontario the great bulk of the species live within 25 feet of the surface.[37]

Temperature has long been known to be an important factor in limiting or modifying the character of a fauna. "Each species is especially adapted to flourish within a particular range of temperature, which differs both in actual degree and extent of range for different species"[38] and all waters of the sea, both cold and warm, are more or less densely populated. Wherever there is sea there is also abundant life," and as a general fact it may be stated that "animal life of all kinds, both in the surface waters and on the bottom, is more dense in the polar regions than it is in intertropical ones,"[39] a large fauna being collected by the British Antarctic Expedition through the ice in Murdo Sound and Ross Sea.[40] The variety of life in the colder waters seems to be less than in the warmer, but it does not seem probable that this fact would be of much advantage in restoring the environment of the fossil forms. Changes of temperature, both with respect to extent and rapidity of change, are of greater importance to organisms than the actual degree of temperature. For each species there is a maximum rate of change which cannot be exceeded without some injury to the organism. Verrill[41] in 1880 called attention to the great abundance of benthonic and other organisms beneath the waters of the Gulf Stream off the coast of New England, and to the great changes[42] and tremendous destruction produced by a storm of the winter of 1881–1882, which is thought to have forced colder inshore waters outward over the bottoms across which the Gulf Stream flowed. The changes in temperature almost eliminated the tile fish in that region, and so decreased the bottom organisms that species abundant in the summer of 1881 in the succeeding summer were scarce or absent.

However, the fact that living organisms are adapted to certain temperature or climatic conditions does not indicate a great deal with respect to

[36] Allen, E. J., On the fauna and bottom deposits near the thirty fathom line from the Eddystone Grounds to Start Point, Jour. Marine Biol. Assoc. U. Kingd., vol. 5, 1897–1899, p. 372.

[37] Kindle, E. M., The bottom deposits of Lake Ontario, Trans. Roy. Soc. Canada, vol. 19, 1925, pp. 17–72.

[38] Allen, E. J., op. cit., p. 372.

[39] Johnstone, J., A study of the oceans, 1926, p. 138. See also Kirk, E., Fossil marine faunas as indicators of climatic conditions, Ann. Rept. Smithsonian Inst. for 1927, 1928, pp. 299–307; Giles, A. W., Pennsylvanian climates and paleontology, Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 1279–1300.

[40] British Antarctic Expedition, Geology, vol. 1, 1914.

[41] Verrill, A. E., Notice of the remarkable marine fauna occupying the outer banks of the southern coast of New England, Am. Jour. Sci., vol. 20, 1880, pp. 390–402.

[42] Verrill, A. E., Evidence of great destruction of life last winter, Am. Jour. Sci., vol. 24, 1882, p. 361.

the temperature conditions under which their fossil relatives lived. With species of all the living marine animal phyla found in all marine waters, both cold and warm, and with a similar wide distribution of land animals, it is idle to assume that extinct relatives of modern forms required temperature and climatic conditions similar to those under which the latter lived. It may be safely concluded that the fossil bones and shells of all animals in their specific and generic relationships indicate little or nothing with respect to the climate of the habitat.

Kindle[43] has compared a collection of seventeen species of gastropods and pelecypods made at Ungava on North Labrador with the entire list of shells known from the Bay of Fundy, about 18 degrees of latitude separating the two localities. Only 63 per cent of the seventeen species occur in the Bay of Fundy.

The faunas of the several parts of the Gulf of St. Lawrence are noticeably different. On the coast of Newfoundland in the summer of 1910 there were places where starfishes were seen in great abundance, whereas in 1909 on Anticosti and the Mingan Islands they appeared to be very rare in all localities studied, but since they grow to normal size on these coasts the conditions must not have been prohibitive. On the coast of Nova Scotia at Arisaig in 1908 benthonic organisms seemed to be extremely scarce. Certain bays on the Mingan Islands and on Anticosti in 1909 and again on Anticosti in 1919 were inhabited by thousands of sea urchins, whereas other bays had few or none. There were slight differences in the sediments of the different bays, differences apparently not adequate to explain the great variations in kind and quantity of population, but there must have been some responsible factors in the physical or other conditions. Near Southwest Point on Anticosti there is an area of the bottom supporting many *Pecten*, and big storms throw their shells on the beach in large numbers. This is the only place on the island where *Pecten* shells are common in materials of the beach; at all other places the shell is rare. The factor responsible for this distribution is not known. Hunt[44] has noted that the sand cockle is confined to sandy shores, and he has stated that were sediments other than sand brought to the shores inhabited by this mollusk, the change in sediments would lead to its elimination.

Kindle[45] has studied the relations between existing benthonic faunas of parts of the Bay of Fundy and the sediments upon which they live. A

[43] Kindle, E. M., Bottom control of marine fauna, as illustrated by dredging in the Bay of Fundy, Am. Jour. Sci., vol. 41, 1916, pp. 449–461.

[44] Hunt, A. E., Notes on Torbay, Rept. Trans. Devonshire Assoc. Adv. of Sci., Lit., and Art, vol. 10, 1878, pp. 186–187.

[45] Kindle, E. M., op. cit., 1916, pp. 449–461.

collection made on a soft, black mud bottom at depth of 2 fathoms was composed of 14 species, and one from hard rocky and sandy bottom in depths of 2 to 6 fathoms gave 26 species; only 3 species were common to the two types of bottom. These are the extremes in types of sediments and also extremes in differences of faunas. Stations with other types of sediments showed faunal relationships correlative to sediment similarities.

Marine currents control the distribution of inorganic and some dead organic sediments. They also have much to do with distribution of temperature, food, and salinity. Currents frequently change direction for shorter or longer intervals, with consequent changes in matter transported and deposited. Petersen[46] has stated that the *Modiola* fauna occurs in those places around Denmark where the currents are sufficiently strong to clean the bottom of sand and mud, leaving a bottom composed of coarse materials to serve as places of attachment for the byssal threads of the *Modiola*.

Some parts of the sea bottom seem to be without organisms. In certain instances this is due to the character of the bottom sediments, and in others to the overlying waters. Huntsman[47] has noted such a barren area off the Cape Breton coast, where the barrenness is due to the rather violent changes of temperature in the overlying waters. Sea bottoms characterized by frequently drifting sands are likely to be without bottom inhabitants, since it is as difficult to maintain an existence on such bottoms as on the drifting sands of a desert, a fact well emphasized by Kindle.[48] Bottoms of this kind appear to be not uncommon off many coasts, and some of the unfossiliferous sands of the past probably accumulated under like conditions. Bottom waters with poor circulation have poorly inhabited bottoms; such is the case at the bottom of the Black Sea, in deep lakes, and in deep holes in the sea bottom.

Kindle[49] has stated that certain portions of the Alaskan coast have the bottom covered with organisms, whereas along the beach at Nome and on the bottoms of 6 to 15 feet depth one may search for hours without finding a single shell. One hundred miles northwest of Nome there are thousands of shells under like conditions of depth. On one side of a peninsula of Greenland, dredging produced shells in large quantities; on the other side

[46] Petersen, C. G. J., The sea bottom and its production of fish food, Rept. 25, Danish Biol. Station, 1918, p. 15.

[47] Huntsman, G. A., Canadian Fisherman, May, 1917; quoted by Kindle, E. M., Jour. Geol., vol. 27, 1919, p. 363.

[48] Kindle, E. M., Cross-bedding and absence of fossils considered as criteria of continental deposits, Am. Jour. Sci., vol. 32, 1911, pp. 225–230.

[49] Kindle, E. M., op. cit., p. 229.

not one could be obtained. These results were obtained for shallow water, but they also exist in deep water, as was shown by the "Albatross" expeditions, which in 1904 and 1905 found the bottoms beneath the Humboldt Current, where it flows along the west coast of South America, covered with vast numbers of organisms, but beyond the western edge of that current there was a belt which was extremely sparsely inhabited.

Organisms group themselves into life societies which are splendidly shown among plants. In such a society a balance has been attained between plants and between animals and plants. As long as the conditions do not change either biologically or physically the society remains stable. As soon as a single component changes, however, the society is likely to be broken up. The English sparrow has disturbed the balance among native American birds in that it has eaten some of the food which native birds would have obtained. When the numbers of the latter decrease, on the other hand, certain insects or plants flourish. The benthos of the waters are much like plants and exhibit somewhat similar societies or groupings. The finding of a certain shell leads to the expectation that others are likely to occur, and similar conditions must have obtained in the geologic past.

Petersen[50] has demonstrated that the bottoms about the Danish coast are characterized by animal communities or societies. Of these he has distinguished eight upon the level bottom composed of fine particles, the most important limiting factors appearing to be depth, salinity, the bottom materials, and temperature. The animal population on any bottom is homogeneous and continuous as far as like conditions prevail.

Variations of faunas with sediments also occur in the geologic column, and it is believed that with investigation illustrations will increase and that many stratigraphic units now interpreted as sequential will be shown to be lateral. On the Island of Anticosti the deposits of the north shore are those which were laid down closer to the land than those of the south, and they contain more sand and mud than the latter. The faunas are considerably different. The Becsie formation on the south side, for example, is characterized by almost countless numbers of a pentamerid brachiopod; whereas the species is almost wholly absent from the rocks of the north shore. In the basal portion of the Ellis Bay formation on the south side several species of brachiopods are abundant in shaly beds; the same beds on the north shore are represented by sandy beds in which these brachiopods are extremely rare. *Atrypa marginalis* is extremely abundant in fine-grained limestones about the middle of the formation, but the impure limestones

[50] Petersen, C. G. J., The sea bottom and its production of fish food, Rept. 25, Danish Biol. Station, 1918; A brief survey of the animal communities in Danish waters, 1924, pp. 343–354.

of the north shore do not appear to have the shell. About the middle of the Ellis Bay formation in the southern exposures is a zone characterized by an abundance of *Parastrophia reversa*, a shell which is found rarely on the north side. In the base of the Jupiter formation in the western exposures is a thin zone characterized by an abundance of *Triplecia insularis anticostiensis*, and yet the species is not known in the eastern exposures. *Beatricea undulata* and *B. nodulosa* are abundant in one horizon of the Vauréal formation and again near the middle of the Ellis Bay formation about 400 feet higher, in each case associated with calcareous-argillaceous sediments. Where were they in the intervening time and why were they not in Anticosti waters?

The position of shells in sedimentary materials is worthy of study, and there need to be known the positions in life and the positions assumed after death under various conditions. Shells in the positions in which they lived indicate quiet waters free from much wave and current action. Bivalve shells in various positions, but not heaped together and known to have accumulated on nearly level surfaces, suggest positions attained in quiet waters by the valves merely falling apart following decay of flesh materials, and in such cases the right and left valves should lie adjacent to each other. According to Richter,[51] the separated bivalve shells deposited in waters subject to wave and current action dominantly have the convex sides upward, provided shapes are elliptical to circular and the margins lie nearly in the same plane, as this position is a stable one in the face of water movement. His observations of shells in North Sea waters and the writer's on many beaches and the adjacent shallow waters are in accordance with the generalization. Exceptions to the rule occur at the swashline, where shells are heaped together, or where shells are deposited over irregular bottoms. Bivalve shells whose margins are in different planes or whose shapes are irregular may have the convex side downward, as pointed out by Richter and noted by Häntzschel[52] for *Exogyra columba*. The positions of fossil shells thus become of importance for determination of tops and bottoms of beds and in this way have application to structural geology.

In connection with animal distribution, those conditions which permit or even favor the existence of an organism should be differentiated from those which do not permit its reproduction. Thus, the Atlantic oyster[53] does not

[51] Richter, R., Die Lage schüsselförmiger Körper bei der Einbettung, Senckenbergiana, Bd. 4, 1922, pp. 105–126; Krejci-Graf, K., Flachseeforschung und Praxis, Natur und Museum, Hft. 3, 1928, pp. 97–105. Fuchs and Andrée state the opposite with respect to arching. See Fuchs, T., Denks. Akad. Wiss., Math.-Nat. Cl., 62, 1895, p. 380; Andrée, K., Geologie des Meeresbodens, Bd. 2, 1920, p. 57. The writer's observations are in line with those of Richter.

[52] Häntzschel, W., Senckenbergiana, Bd. 6, 1924, pp. 223–225.

[53] Louderback, G. D., Rept. Comm. on Sed. Nat. Research Council, 1924, p. 59.

reproduce in San Francisco Bay, yet it thrives there after a certain growth has been attained.

Places of absence of fossils in association with other places of great abundance are well known in the geologic column. It is not safe, however, to assume that the former represent barren sea bottoms. They might have been such, but, on the other hand, the shells which were once there may have been repeatedly eaten by animals of the bottom so that they became reduced to fine mud.

On the pages which follow are considered the environmental relations of the different phyla of organisms to the sediments upon which they live, and to those conditions responsible for the development of the sediments in which the organisms may be entombed and of which they are a part.

PLANT RELATIONS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS[54]

Every student of plants knows that they are closely related to the environments in which they occur. One goes to fresh-water marshes to obtain cat-tails, to warm marine marshes for mangroves, to uplands for most of the oaks, and to marine waters for giant seaweeds. Interpretation of fossil plants in an effort to restore the environment requires care in ascertaining whether or not the plants actually dwelt near the places where the fossils occur. Plant matter floats readily, and may be carried many miles from the places of growth. Thus, Agassiz,[55] Murray,[56] and others have reported terrestrial plants on deep-sea bottoms far from land. It naturally follows that transported plant material bears little relation to the environment in which it is deposited so far as kinds of plants are concerned, but the fact of transportation throws light on the environment of deposition, and every occurrence constitutes a distinct problem which must be solved on the basis of associations. Plant matter of long transportation is likely to be badly damaged, with several kinds of plants present, and the association will be one that may be impossible in any environment, whereas if the association of plants is a natural one, short transportation is suggested, with an environment close at hand to which the association is adapted.

Of the lower plants preserved fossil, the non-calcareous marine and freshwater algæ are of little value for interpretation of sediments, as preservation ordinarily is so poor as to make identification difficult or impossible. Lime- and magnesia-precipitating algæ, as modern *Lithothamnium*,[57] *Halimeda*,

[54] Berry, E. W., Environmental interpretation of fossil plants, Pan-Am. Geol., vol. 38, 1922, pp. 9–17. Much of what follows has been taken from this paper.

[55] Agassiz, A., Mus. Comp. Zool., vol. 14, 1884, p. 391; vol. 21, 1891, pp. 187–197; vol. 23, 1893, p. 12.

[56] Murray, J., Deep sea deposits, Challenger Rept., 1891, pp. 94–101.

[57] For a careful and authoritative consideration of the rôle of plants, particularly algæ, in rock building the reader should consult Pia, J., Pflanzen als Gesteinsbildner, Berlin, 1926.

Penicillus, *Chara*, *Lithophyllum*, *Corallina*, etc., and ancient forms, like *Cryptozoon*, *Collenia*, *Sphaerocodium*, *Physoporella*, etc., indicate clearness of water and depths not greater than the penetration of light. They prove little with respect to salinity, as modern forms dwell in both fresh and salt waters, but seemingly in waters highly charged with lime. The majority and greatest variety of existing forms appear to be confined to marine or saline waters, and their greatest deposits seem to have been made under such conditions; but there appear to be no good reasons why they may not have had wide distribution in the fresh waters of past geologic periods, and their extensive occurrence in the Proterozoic of North America, and probably other continents, cannot be considered proof that the containing strata are of marine origin. It is probable that they always have had greatest distribution and abundance in warm or tropical waters, but this also remains to be established, as some forms are extremely common in cold temperate waters over many parts of the world.

Lower forms of plants are diatoms and bacteria, neither seemingly indicating a great deal in terms of conditions of environment. This seems to be mainly due to ignorance of the limiting environmental conditions of particular forms, since they cannot be independent of environmental control. Bacteria dwell everywhere in forms and abundance correlated to environmental conditions, but identification of fossil forms is almost impossible. Many diatoms are planktonic and hence are transported into many environments.

The higher plants are mostly terrestrial, and most species are closely related to the environments in which they occur. Fossil forms may or may not have living representatives, and in any event, the latter, unless possessing diagnostic adaptive characters, are of little aid for interpretation of sedimentary environments. Furthermore, in dealing with fossil plants distantly related to living species, caution is essential, as it does not follow that the fossil forms dwelt in the same environments as their living relatives. Where kinship to living forms is close, and the latter are adapted to a wide environmental range, it is not safe to draw any conclusions relating to environments of the fossil forms. Where the related living forms are limited to narrow environments, however, more confidence may be had with respect to the conditions under which the fossil forms lived.

Lagoons, small lakes, and other bodies of water whose sediments are local and whose shores are low receive the greater portion and perhaps all of their vegetable matter from the immediate vicinity. As the waters are little disturbed, the plant matter may be well preserved and is apt to have a community of ecologic characters. Narrow bays, bayous, and small lakes may have very poor circulation of water and become antiseptic as a consequence. This assists in the preservation of leaves.

Small lakes in mountain regions have shores of considerable relief; a variety of environments is close to water; and there are excellent opportunities for mixed associations of plant materials. These could be differentiated from the deposits of small bodies of water with low shores on the basis of the mixed associations, and from others of mixed association on the bases of excellent preservation and the presence of delicate structures. As many mountain regions have volcanoes, an ash shower may cover a lake nearby and bring floating leaves to the bottom in large quantity, leading to excellent preservation of all the floating matter carried down. This is exemplified by the leaves and insects exquisitely preserved in the Florissant shales of Colorado.

The deposits of deltas may receive vegetable matter from many parts of the regions drained. Some plant matter will have been derived from nearby, whereas much will have come from regions drained by the headwaters, the latter consisting largely of those parts of the plants best able to withstand long journeys, as nuts, logs, branches, etc. Leaves so transported usually are without the tips and petioles and have frayed edges. The association has no ecologic community, and there are almost certain to be great differences between the plants of this association and those deposited in one of the bayous of the flood plain or a lagoon of the delta.

Thus, deposits with well preserved leaves of a community of ecologic characters suggest the environment of a small lowland lake, lagoon, or bayou; deposits with well preserved leaves showing mixing of ecologic characters suggest the environment of a mountain lake; and deposits containing plant materials from several environments, with leaves considerably mutilated and with much resistant plant material, suggest the environment of a flood plain or delta.

Where trees occur in places of growth, as in the Joggins section of Nova Scotia, or where the stumps are found below coal beds with the roots in the underclay, the interpretation of the original environment may be made from the types of plant growth and the ecologic adaptations.

The adaptive characteristics of plants and the positions of plant matter in sediments give much aid in interpretation. Wind-laid material is dry, and as a consequence leaves are rolled or curled, hard fruits have lost their outer coats, and cones have their scales separated. Leaves and fruits in such sediments are not as a rule deposited parallel to bedding, but are jumbled together. In water-laid deposits, on the contrary, both leaves and fruits are apt to lie parallel to bedding, and cones have many or most of the scales in contact. These differences may be seen in the Lower Cretaceous Cheyenne sandstone near the village of Belvidere, Kansas, where vegetable matter occurs both in sands and clays. In the clays the leaves lie parallel to bedding; whereas in the sands, which appear to be of wind deposition,

the leaves are curled, and cones which are present have the scales separated.

Plants of arid regions are characterized by leaves of small size, curled margins, waxy surfaces, palisade tissue, and reduced stomata. Many possess spines. Caution is necessary here, however, as some of these structures result from physiological dryness due to an excess of salts in the substratum or some other factor, so "that xerophytic structures are not necessarily confined to xerophytic situations."[58] The plants of arid regions are also characterized by the possession of one of two types of roots, either a deep tap root extending downward to ground water and characteristic of the perennials, or a horizontal root system noteworthy in annuals. However, neither of these features, nor the association, is confined to this environment, as both occur in regions of rainfall, where, however, there are also plants with roots penetrating intermediate parts of the ground.

The plants of wet and swampy environments may possess lacunate roots, such as were characteristic of the Paleozoic *Calamites*; a horizontal root system, very marked in balsams, spruces, cedars, and other trees living in this environment; knees, as in the cypress; or enlarged boles, as in *Taxodium*. Long tap roots are not probable in the swamp environment, and leaves of swamp plants usually have abundant and delicate stomata.

RELATIONS OF PROTOZOA TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

The problem is concerned only with radiolaria, silicoflagellata, and foraminifera, as other forms do not seem to be preserved. Radiolaria are exclusively marine and planktonic and hence have wide distribution. Their siliceous shells make significant deposits only in those places where other sediments are in quantities so small as not to mask the shells, but they probably are present in minor quantity in the deposits of most, if not all, marine environments. Their significant presence is likely to be limited to bottoms far from land and in depths so great that calcareous planktonic shells are largely dissolved before reaching bottom, but not so deep as to cause the siliceous shells to go into solution before the bottom is attained. This condition places distribution between about 12,000 and 20,000 to 25,000 feet. It may be possible for radiolarian shells to make a large part of a deposit in shallow waters, as the radiolaria-containing sediments of Barbados and Trinidad, the radiolarites of the Alps, and the siliceous shale of the Pico formation of California.[59] The conditions permitting radiolaria to make a large part of a shallow-water deposit would, however, be exceptional

[58] Coulter, J. M., Plants, 1902, p. 208.

[59] Reed, R. D., A siliceous shale formation of southern California, Jour. Geol., vol. 36, 1928, pp. 342–361.

and the deposit local. The occurrence of radiolarian shells in significant quantity and over a considerable area is thus considered to suggest depths from about 12,000 to 25,000 feet. In their present distribution radiolaria are most abundant in tropical waters, and their significant occurrence in sediments suggests warm climates during the times of accumulation.

The silicoflagellata[60] are marine and pelagic, and may have wide distribution. Little is known relating to their occurrence in sediments and about as much respecting their relations to ecologic conditions. They have been identified from the Tertiary of Sicily and the Upper Cretaceous Moreno shale and the Tertiary Pico formation[61] of California. Presumably they have been deposited in all marine deposits since their first appearance. It is not known that the silicoflagellate tests are responsible for a large part of any sedimentary unit.

Foraminifera[62] live in both marine and fresh waters, but so far as known, fresh-water forms do not occur as fossils and need not be considered. Shells are mostly calcareous, but some are composed of siliceous materials, chiefly cemented sand grains. Recent marine foraminifera may be divided into two groups: one belonging to the plankton and having wide distribution, the other benthonic and living upon the sea bottom. The greater number of species is found in the latter group. The shells of the former are small, have high competency, and are composed of calcium carbonate. Shells of some benthonic forms, as the extinct *Nummulites*, are relatively large. The planktonic forms make deposits to depths of about 14,000 to 15,000 feet and occur to some extent in the accumulations of greater depths. They constitute a large and frequently the major portion of *Globigerina* ooze and are more or less abundant in deep-sea oozes to the depths given above.

Accumulations of sediments of which pelagic foraminifera constitute large portions are ordinarily made considerable distances from land, but when ocean currents are suitably directed, or the conditions are such as to limit the quantity of terrigenous sediments or sediments of organic origin, the shells of pelagic foraminifera may accumulate in such quantities as to make a deposit in very shallow water or even upon the beach, as occurs upon Trinidad, where some of the sands are almost exclusively *Globigerina* shells.

[60] Hanna, G. D., Silicoflagellata from the Cretaceous of California, Jour. Paleont., vol. 1, 1928, pp. 259–263, pl. 41. Hanna cites all references known to him.

[61] Reed, R. D., op. cit., p. 350. Merely notes their presence.

[62] For detail relating to foraminifera, the writings of Cushman, J. A., Vaughan, T. W., and Galloway, J. J., should be consulted. The writer is indebted to Doctor Cushman for considerable data. See also Norton, R. D., Ecologic relations of some foraminifera, Bull. Scripps Inst. Oceanography, Tech. ser, vol. 2, 1930, pp. 331–388.

Bottom-dwelling foraminifera are rather closely limited by depth and temperature, the latter probably having the greater influence. Certain species which occur in tropical regions in deep and therefore cold waters are found in shallower depths in higher latitudes, whereas species living in the comparatively shallow waters of tropical regions have limited distribution north and south, excepting as they occur beneath warm currents. Forms of higher latitudes show similar relationships, that is, rising to shallower depths in poleward directions. Benthonic foraminifera are both vagrant and sedentary. Some favor muddy bottoms; sandy and gravelly bottoms as a rule have few species; bottoms covered with seaweeds and grasses may have an abundant population.

Benthonic foraminifera of most importance in modern marine sediments occur in shallow tropical waters. Their accumulations are somewhat extensive to depths of 30 fathoms in waters with temperatures ranging upward from 75°F. Similar conditions are suggested for benthonic foraminiferal deposits of the geologic past, the suggestion having greater validity the nearer the kinship of the fossil forms to those now living; and on this basis the Cretaceous and Tertiary deposits containing abundant benthonic foraminifera are assigned to a warm shallow-water environment. Another factor influencing the distribution of benthonic foraminifera is the alkalinity of the waters in which they live, and many forms under conditions of high alkalinity have calcareous tests which are heavy in comparison to the quantity of protoplasm in the organism. In acid waters, such as occur in stagnant bays and at great depths, foraminifera often develop chitinous tests instead of the normal calcareous ones.

The fragility of foraminiferal shells militates against their occurrence in coarse materials and the deposits of turbulent waters. Sands of protected bays and beaches, on the other hand, may contain them in considerable quantities, as exemplified by the celebrated Dog Bay sands of the Irish coast. In the tropics the beach materials of protected bays not infrequently consist very largely of worn shells of foraminifera.

Certain families are characteristic of particular environments. The Nummulitidæ and some of the larger Rotaliidæ are very characteristic of warm tropical waters in depths less than 30 fathoms. The much smaller Miliolidæ thrive under similar conditions, but the family is not confined to warm waters, some genera being present in polar regions. The Lagenidæ, particularly the larger genera such as *Nodosaria*, *Cristellaria*, *Frondicularia*, etc., seem to be most characteristic of waters of medium temperature, such as are found from 100 to 500 fathoms. The Globigerinidæ, largely pelagic, make up the great mass of deposits at depths of 500 to 2000 fathoms, especially in tropical and subtropical waters.

Briefly, then, the facts indicate that foraminifera are adapted to several of the factors of sedimentary environments. Their presence suggests marine deposits. Certain forms suggest the pelagic environment and deep-water deposition. Large, massive forms indicate a benthonic habitat on warm, shallow bottoms. Small benthonic forms indicate little with respect to temperature, and may have lived in depths as great as 500 fathoms.

RELATIONS OF SPONGES TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Sponges belong to the sedentary benthos and attain greatest development in warm and clear waters, in which they occur to great depths. They are least common on muddy bottoms, and such seems to have been their past distribution, as the great sponge horizons occur mostly in limestones. Some ancient sponges certainly lived on muddy bottoms, as exemplified by the Dictyospongidæ colony in the New York Devonian. Recent sponges occur both in marine and fresh waters, but fresh-water species are few and none seems possible of fossilization.

Thus, an abundance of sponges implies warm, marine waters, but the group has little value for interpretation of sediments and reconstruction of sedimentary environment because of rarity of occurrence, difficulty of identification, and ignorance of the significance of particular species.

RELATIONS OF CŒLENTERATES TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Cœlenterates are almost exclusively marine. A few, both medusoid and vegetative forms, live in fresh water, but fresh-water species are without skeletal support and are not likely to leave fossil evidence. It is assumed that fresh-water forms of the past, if there were such, were similar to those of the present. Fresh-water forms, hence, need not be further considered. Except for the lime-secreting hydroids and forms like the ancient graptolites, hydrozoans are not of common occurrence in the geologic column and are of small service in the interpretation of sediments. Most benthonic hydroids, particularly the lime-secreting species, belong to the shallow waters, but some extend to considerable depths. Deep-water forms belong mostly to the Plumularians,[63] known to extend to a depth of 2240 feet. They do not seem to thrive on muddy bottoms or in waters in which there is much turbidity.

The Paleozoic graptolites appear to have had two modes of life. Dendroid forms probably grew attached to either fixed or floating objects; true graptolites either had floating organs to support the colonies, or they became attached to fixed or floating objects. Thus, some forms belonged to the

[63] Agassiz, A., Three Cruises of the 'Blake,' vol. 2, 1888, p. 35.

benthos, and others were planktonic or epiplanktonic. The non-benthonic habit makes wide distribution possible. Graptolites occur in abundance mostly in dark to black shales, an association best explained on the basis that this type of rock was deposited under reducing conditions in waters considerably antiseptic or poisonous, with the bottoms inhabited by few organisms, particularly scavengers. Graptolites sinking to such bottoms had excellent chances of being preserved. On bottoms overlain by oxygen-bearing waters and in the waters themselves, the delicate colonies of graptolites probably lived in greater abundance than elsewhere, but their remains had little chance of persisting to permanent burial because of abundance of scavenger organisms. (See discussion of black shales.)

TABLE 19

THE NUMERICAL DISTRIBUTION OF FORMS ACCORDING TO DEPTH

	DEPTH IN FATHOMS											
	0–25	25–40	40–100	100–200	200–300	300–400	400–500	500–600	600–700	700–800	800–900	900–1150
Number of forms at that depth	77	14	7	21	13	8	0	0	1*	0	2	1
Number of forms confined to that depth	70	5	2	14	13	5	0	0	0	0	1	1
Number of forms ranging into the next deeper	7	2	4	5	3	0	0	0	0	0	0	0
Number of forms occurring in next shallower	0	7	2	4	5	3	0	0	0	0	0	0
Number of forms in both shallower and deeper water	0	0	1	2	1	0	0	0	0	0	0	0

* Also collected between 800 and 900 fathoms.

The anthozoan corals are those most important to the student of sediments. Here the growths are greatly influenced by the nature of the bottom and the clearness of the waters, bottoms overlain by clear waters and with objects to which the corals may attach themselves being most conducive to coral growths. Muddy and sandy bottoms have few corals, and waters that contain much suspended sediment have a restricted coral growth, with the colonies divided into upward-pointing branches with few surfaces upon which sediment may lodge.[64]

Depth has a great influence on corals, as is shown by tables 19 and 20,

[64] Vaughan, T. W., Corals and the formation of coral reefs, Ann. Rept. Smithsonian Inst. for 1917, 1919, p. 202. See also by Vaughan, The oceanographic point of view, Contributions to marine biology, Stanford Univ. Press, 1930, pp. 44–56.

in which are given the bathymetric distributions of the Madreporaria of the Hawaiian Islands and Laysan.[65]

The corals of the deeper waters are smaller and far more delicate in structure than are those of the shallower waters, the strength of the coral colony

TABLE 20

BATHYMETRIC DISTRIBUTION OF THE GENERA

(Depths in fathoms)

0–25	25–40	40–100	100–200
Pocillopora	Pocillopora	Madracis	Flabellum
Leptastrea	Pavona	Fungia	Placotrochus
Cyphastrea	Leptoseris	Leptoseris	Paracyathus
Cœlastrea	Montipora	Stephanophyllia	Deltocyathus
Fungia	Porites	Balanophyllia	Caryophyllia
Pavona			Cyathoceras
Leptoseris			Anthemiphyllia
Stephania			Madracis
Psammocora			Leptoseris
Dendrophyllia			Stephanophyllia
Montipora			Endopachys
Porites			Balanophyllia
Alveopora			Dendrophyllia
200–300	**300–400**	**400–500**	**500–600**
Flabellum	Desmophyllum	None	None
Gardineria	Caryophyllum		
Desmophyllum	Cyathoceras		
Paracyathus	Madrepora		
Trochocyathus	Mussa?		
Caryophyllia	Anisopsammia		
Cyathoceras			
Madracis			
Leptoseris			
Anisopsammia			
600–700	**700–800**	**800–900**	**900–1150**
Flabellum	None	Flabellum	Bathyactis
		Caryophyllia	

being somewhat inversely proportional to depth, the same species being slender and fragile in deep and quiet waters and stout and strong in shallow

[65] Vaughan, T. W., op. cit., 1919, pp. 37, 39.

and agitated waters.[66] The tables probably are incomplete, but they represent present knowledge. They show that twice as many forms live in depths up to 25 fathoms as in all depths below, and that none is known below the depth of 1150 fathoms, although it is possible that some may be present. A second zone of maximum distribution exists between 100 and 200 fathoms which contains one less than the number of genera in the topmost zone, but only about one-third as many species. The distribution shows something

TABLE 21

DISTRIBUTION WITH RESPECT TO TEMPERATURE*

Pocillopora	Flabellum†	Flabellum	Flabellum	Flabellum
Leptastrea	Placotrochus†	Cyathoceras	Gardineria	Caryophyllia
Cyphastrea	Paracyathus†	Madracis	Desmophyllum	Bathyactis
Cœlastrea	Caryophyllia†	Stephanophyllia	Paracyathus	
Favia	Cyathoceras†	Balanophyllia	Deltocyathus	3 forms
Fungia	Anthemiphyllia†		Trochocyathus	
Pavona	Madracis‡	7 forms	Caryophyllia	
Leptoseris	Fungia‡		Cyathoceras	
Stephania	Leptoseris		Ceratotorchus	
Psammocora	Stephanophyllia†		Madrepora	
Dendrophyllia	Balanophyllia§		Madracis	
Montipora	Dendrophyllia§		Mussa? young?	
Porites			Leptoseris	
Alveopora	19 forms		Stephanophyllia	
			Endopachys	
70 forms			Balanophyllia	
			Dendrophyllia	
			Anisopsammia	
			21 forms	

* Vaughan, op. cit., p. 45.

† Not obtained at a temperature as high as 70°.

‡ Not obtained at a temperature as low as 70°.

§ Temperature range doubtful.

of a cyclic arrangement. From nothing to 100 fathoms there is a rapid decrease in number with depth, seventy-seven in 0 to 25 fathoms as against twenty-one in 25 to 100 fathoms. There is then a rise to twenty-one species in depths of 100 to 200 fathoms, followed by a decline to essential disappearance at 400 fathoms. No species occurring between 100 to 400 fathoms ranges into deeper waters, and only four certainly occur in shallower waters

[66] Vaughan, T. W., op. cit., 1919, p. 196.

The reef-building forms are almost wholly confined to depths of 0 to 25 fathoms.

The second important factor controlling the occurrence of corals is temperature. Table 21 shows the distribution with respect to this factor in Hawaiian waters.

The greatest abundance of corals about Hawaii is found between temperatures 73° and 78° F. and in depths up to 40 fathoms. The temperature of 73°F. appears to be the dividing line between shoal and deep-water forms. A second zone of abundance occurs between the temperature range of about 70°F. and about 40°F., with depths of 100 to 400 fathoms. Below 30°F. corals are not present.

North of the coral-reef areas the low-temperature forms seem to live in shallower waters.[67]

Living reef corals may endure a temperature as low as 64°F. (18.15°C.),[68] but it is not probable that they would live for a very long time, and about 68°F. probably represents the lower limit at which they thrive. Where depths are such as to bring the waters below this temperature, reef corals are wanting. Such is their present distribution, and as Tertiary and Mesozoic genera are more or less closely related to present forms, it is not unlikely that such has been the distribution since the development of modern types. Whether the Paleozoic reef-building Tabulates, Heliolitidæ, Rugosa, Stromatoporoidea, and Archæocyathidæ required like temperature conditions cannot be stated. Independent evidence proves that the waters were generally shallow, and there is no positive evidence indicating low temperature, but, on the other hand, there are no facts, independent of the corals, proving high, or even moderately high temperatures.

An excellent illustration of the response of corals to different physical conditions is given by their distribution in the lagoon and on the reef about the Cocos-Keeling Islands of the West Indies. Twenty-three species were collected from the lagoon, twenty in the barrier pools and the barrier flat, and sixteen on the exposed barrier. Of the twenty-three species of the lagoon, three occur on the exposed barrier, and one of these is so modified to meet the physical conditions existing there that it is with difficulty identified as identical with the lagoon form. Thirteen per cent of the species of the lagoon are on the exposed barrier, and 18 per cent of the species of the barrier are found in the lagoon. The lagoon and the exposed barrier are within a half mile of each other, and within this short distance there is this great difference in coral fauna. It must be remembered that these two faunas are contemporaneous, and that the ratio in each case is less than

[67] Vaughan, T. W., op. cit., 1919, p. 200.
[68] Vaughan, T. W., op. cit., 1919, p. 201.

one-fifth. Of the twenty species in the barrier pools and the barrier flat, six also occur within the lagoon and two on the exposed barrier. That is, 10 per cent of the species of the barrier flat occur upon the exposed barrier and 30 per cent in the lagoon. The barrier flat is between the exposed barrier and the lagoon, and yet it does not have a majority of its species

TABLE 22

	FREE CORALS	FRAGILE BRANCHES OR FOLIA	STOUT BRANCHES AND LOBATE COLUMNS	GROWTH FORM MASSIVE
Lagoon	2	11	5	5
Barrier pools and barrier flat	2	6*	4	8
Exposed side of barrier			3	13

* Mostly on lagoon edge of flat.

TABLE 23

DISTANCE FROM SHORE	DEPTH OF WATER AT LOW TIDE	CHARACTER OF BOTTOM	NUMBER OF SPECIES AT EACH STATION	NUMBER OF SPECIES ACCORDING TO GROWTH FORM		
				Free disks and fragile branches	Stout branches	Massive or encrusting
feet	*inches*					
300	2–4	Hard limestone mud over lava rock	1	0	0	1
400	4.5–5	Firm limestone mud	7	3	0	4
450–550	6–12	Sand and mud, rock	10	3	0	10
600–650	6.5–10	Sandy	18	7	0	11
800–820	10–11	Broken coral	20*	6	1	12
1000–1020	14–17	Rocky	21	10	1	10
1200–1250	14–16	Rocky	18	6	2	10
1400–1445	14–15	Rocky, broken coral	24	10	2	12
1660–1675	10–16	Hard, rocky, broken coral	32	4	2	26
1720–1775	2.5–3	Hard, rocky, with crevice-like tide pools	13	0	6	7

* *Acropora palmata* is not counted in the tabulation.

common to either the lagoon or the exposed barrier.[69] It is probable that were these differences found in the geologic column, unconformities would be postulated to explain the situation.

Although the species in these three different environments are greatly

[69] Vaughan, T. W., Fossil corals from Central America, Cuba and Porto Rico, etc., Bull. 103, U. S. Nat. Mus., 1919, p. 192.

unlike, there are almost equal differences in the shapes of the colonies, as shown by table 22, in which is given the distribution of the shapes of the corals in the three environments.[70]

Corals from Murray Island, Australia, have adaptation to environments as shown in table 23. The character of the bottom suggests the extent of wave activity.[71]

An example from the geologic column which seems to illustrate adaptation to wave activity is shown in the distribution of *Paleofavosites prolificus* and *P. capax* from the Anticosti section. The former is generally distributed through limy muds and limestones; the latter reached its best development on sandy bottoms. The corallites of the latter are two to three times the diameter of those of the former.

In general, reef corals imply, if they do not prove, clear, warm, and shallow marine waters. Delicate forms in isolated individuals and small forms imply deep waters. Heavy forms with strong coralla imply waters which were strongly agitated at times. An abundance of species and individuals implies waters which were shallow.

Non-colonial forms mean little or nothing with respect to temperature, as these are now found in cold as well as warm waters, and such probably was also the case during the past geologic periods.[72]

RELATIONS OF BRYOZOA TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Most bryozoa are marine; a few live in fresh water, but are without skeletal support, hence have little or no chance of preservation and are without significance for the student of sediments. Most marine bryozoa possess shells. The majority live in shallow water, but some species extend to great depths. They seem to occur in greatest abundance in tropical and warmer temperate waters.

According to Bassler,[73] little has been done on the significance of bryozoa

[70] Vaughan, T. W., Corals and the formation of coral reefs, Ann. Rept. Smithsonian Inst. for 1917, 1919, pp. 195–196.

[71] Vaughan, T. W., op. cit., 1919, pp. 195–196.

[72] On the distribution of modern corals in cold as well as deep waters reference should be made to Pratje, O., Korallenbänke in tiefem und kühlem Wasser, Centralblatt f. Min., Geol., und Pal., 1924, pp. 410–145. In this paper it is shown that reef corals are now living on the west European coast from Spain nearly to the northern end of Norway. To appreciate the magnitude of coral deposits in existing seas the book by W. Saville-Kent on the Great Barrier Reef of Australia, London, 1893, should be consulted. The deposits of this reef extend over an area estimated to exceed 80,000 square miles. A more recent work on the Great Barrier Reef is that of Yonge, C. M., A year on the Great Barrier Reef, New York, 1930.

[73] Bassler. R. S., Letter to T. Wayland Vaughan, June 5, 1922.

with respect to the physical conditions so far as these relate to sediments. He states:

> Bryozoa feed mainly upon planktonic organisms and thrive unusually well in brisk currents. However, areas with moving sands are not favorable for the growth of bryozoa because the animal requires a larger and steadier object than a sand grain for the attachment of its larva. The larvæ easily attach themselves to larger rocks and therefore a rocky bottom swarms with encrusting bryozoa. Muddy bottoms are very poor in bryozoa, but shell marls, where the shell serves as a substratum to the encrusting species, are exceedingly rich in them. The erect bryozoa generally attach themselves to ascidians or to sea weeds and so such species are often indicative of the great marine meadows.

In general, it may be concluded that bryozoan remains suggest shallow marine waters of temperate and tropical conditions. Due to the smallness of bryozoan remains, their incorporation in the sands of seashore dunes may be expected.

RELATIONS OF BRACHIOPODS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Living brachiopods are exclusively marine, and there is nothing suggesting that the sea has not always been the home of the phylum. The present oceans contain one hundred and fifty-nine identified species, of which five are restricted to the strand-line, three of these being inarticulates and two articulates. Forty-four species range from the strand-line to a depth of about 90 feet. Twenty-one of these are inarticulates and twenty-three articulates. Sixty-three species range from 90 to 700 feet; only seven of these are inarticulates. Seventeen species, all articulates, range from 600 to 1000 feet. The remaining species are found in depths greater than 1000 feet. There is thus a decline of inarticulation with depth. All deep-water species have thin fragile shells and are small, or at least smaller than the shallow-water species of the same genera.

The inarticulate species, of which there are twenty-nine, are mostly confined to waters of less depth than 600 feet. There is only one wholly deep-water form, and this is known to extend to a depth of 14,450 feet. Many of the linguloids seem to prefer waters which have a salinity below normal, as they appear to like bays and estuaries which receive additions of fresh water. The thick-shelled inarticulates belong to the very shallow waters, and their abundant occurrence suggests bottoms not deeper than 100 feet.

Of the one hundred and twenty-nine species of articulate brachiopods, twenty-five live on bottoms shallower than 90 feet, and fifty-nine occur on bottoms between 90 and 600 feet in depth. Only two species appear to be restricted to the strand. There are twenty-nine species of articulates in waters of depths exceeding 13,000 feet. All of these have thin fragile shells which are more or less transparent and generally small. The shallow-water

forms have larger and thicker shells, and they are far more abundant both in species and individuals. A rather characteristic feature of shallow-water brachiopods is the presence of healed shells, which may have been broken by predatory animals or by wave action.

In general, therefore, brachiopods in shallow water have strong and thick shells, and are abundant in species and individuals; deep-water forms have thin and fragile shells, which average smaller in size than those of shallow water, and are fewer in individuals and species.

Lingula and *Discina* are characteristic of shallow waters from the strand line to about 60 feet. *Discinisca* is also in shallow waters but extends to over 200 feet depth. *Crania* has a range from about 12 to over 4800 feet. Modern rhynchonelloids with fifteen species live from shallow waters to depths exceeding 12,000 feet, and the abundant terebratuloids with one hundred and twelve species are mostly confined to shallow waters, seventy-six species living in waters less than 600 feet deep.[74] The present ecologic distribution appears to be in harmony with the distribution in the past, except with respect to rhynchonelloids, of which the fossil forms had great development in shallow waters.

Not a great deal appears to have been done with respect to the adaptation of brachiopods to materials of the sea bottom. Brachiopods with pedicle openings and pedicles must have required solid bottoms or bottoms with solid objects for pedicle attachment. These are the orthoids, most strophomenoids, pentameroids, rhynchonelloids, atrypoids, terebratuloids, spiriferoids, and athyroids. On the other hand, the linguloids, discinoids, certain of the strophomenoids, and particularly some of the productoids, are known to have lived on muddy bottoms as do some of the linguloids today. The pentameroids in particular indicate clear waters free from suspended sediments, and the various Pentamerus bands of the Silurian and basal Devonian suggest clear waters near low shores, or at some distances from high shores.

The Derbyas of the West Virginia Pennsylvanian, studied by Price[75] with respect to adaptation to sedimentary conditions, showed that the shells of smallest dimension occur in black sediments, those of medium to large size in more calcareous beds, as sandy black shales and limestones, and the larger shells of *D. crassa* and small to large *D. robusta* occur in light-colored shales without much sand and in the light-colored argillaceous limestones.

[74] Schuchert, C., Paleogeographic and geologic significance of recent Brachiopoda, Bull. Geol. Soc. Am., vol. 22, 1911, pp. 258–275. The data given above have been largely taken from this paper.

[75] Price, W. A., Maximum size of West Virginia Derbyas as influenced by sedimentation, West Virginia Geol. Surv., Webster Co. Rept., 1920, pp. 545–551.

Kingina wacoensis of the Texas Washita has been described as having had a very local distribution and having shifted its habitat because of very close adaptation to environmental factors.[76]

More should be known respecting the living positions of brachiopods in order to evaluate their positions as they occur in the sedimentary formations. Öpik has noted that in the Kuckers formation of Esthonia a species of *Lingula* stands perpendicularly, with the beak directed downward, and that the equiconvex *Porambonites* holds a like position, and his figures show a *Clitambonites* similarly placed. These are interpreted as the life positions of the organism.[77]

It is very probable that most brachiopods in their present distribution have close adaptation to different environments, and such is also likely to have been true for ancient species. These adaptations must be known before accurate correlations on the basis of the group are possible.

RELATIONS OF ECHINODERMS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Of the seven divisions of the echinoderms, the asteroids, ophiuroids, and holothuroids are so rare in the geologic column as to give little aid in interpretation of sediments. These forms are vagrant benthos. Many seem to prefer muddy and sandy bottoms. They range to depths of about 2,000 feet.

Echinoids live upon muddy, sandy, and solid bottoms. Some species find conditions most desirable on sandy bottoms; others prefer bottoms of fine muds. Still others live on rocks into which they drill cavities for themselves, or live in crevices. They have a somewhat discontinuous or colonial distribution, and such appears to have been the case for some of them in the past, as exemplified by the Mississippian *Melonites*. Most echinoids live in very shallow water; a few species descend to bottoms as deep as 18,000 feet.

Benthonic crinoids, blastoids, and cystoids imply clear water free from much suspended sediment. As, however, some Paleozoic and later crinoids and some cystoids were not attached to the bottom or became detached at some stage of life to become planktonic,[78] it is not altogether certain that a crinoid or cystoid is indicative of habitat, as floating forms must have died

[76] Sandidge, J. R., The recurrent brachiopods of the Lower Cretaceous of northern Texas, Am. Jour. Sci., vol. 15, 1928, pp. 314–318.

[77] Öpik, A., Brachiopoda Protremata der Estländischen Ordovizischen Kukruse-Stufe, Acta et Comment. Univ. Tartuensis (Dorpatensis), A XVII, 1, 1930, pp. 39–41.

[78] Kirk, E., The structure and relationships of certain Eleutherozoic Pelmatozoa, Proc. U. S. Nat. Mus., vol. 41, 1911, pp. 1–137; Contrib. Geol. Dept., Columbia Univ., vol. 21, No. 6.

over every type of bottom and become incorporated in every type of sediment. Modern crinoids range from shallow water to about 12,000 feet; one species has been obtained at a depth of 14,000 feet. In general, stalked forms require waters sufficiently deep to be protected from waves. Crinoids in the past appear to have lived in colonies on the sea bottom as exemplified by the fame of certain localities where they are abundant, and many collectors know of spots where it is easy to find them. As blastoids and cystoids are extinct, the depths of water in which they lived must be determined by the associations.

Echinoderms are, and probably always have been, exclusively marine organisms. Their fossil remains thus constitute an easy method of differentiation between marine and continental deposits, particularly as every fragment of an echinoderm behaves optically as a calcite crystal with typical calcite cleavage.

RELATIONS OF PELECYPODS AND GASTROPODS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Mature pelecypods and gastropods, so far as they are aquatic, belong almost exclusively to the benthos. Most are vagrant; some are attached. The majority live in the sea, but many species flourish in fresh water, and there are certain genera which have representatives in both fresh and salt water. The majority of marine forms live in shallow water. Many gastropods are terrestrial and some pelecypods live buried in mud or sand. Some forms have narrowly restricted limits, as, for instance, the pelecypod *Mytilus edulis*, which lives in the shore zone exposed at low tide, and *Modiola plicatula*, which is fond of salt marshes, where the salt water may cover it for a short time during each high tide. On the other hand, a very closely related species, *Modiola modiola*, must have a permanent cover of salt water. The gastropod *Littorina* lives in the tidal zone, where it is exposed a great deal of the time, and it even ventures into fresh-water streams. Certain pelecypods, as oysters, must have a hard bottom or a bottom with solid objects to which they may attach themselves; they never occur on soft mud bottoms. The bathymetric ranges of pelecypods and gastropods are very great. In general, the shells of shallow-water forms, exclusive of those pelecypods living in the muds, are thick and heavy, whereas shells of deep-water forms are thin, fragile, and frequently transparent. Some species appear to be able to endure a variety of conditions, but, in general, there is a close relation to environment.

Too little seems to be known with respect to pelecypod and gastropod adaptation to environment; and the number of species of each phylum, and their great variety, render dangerous any statement applicable to any particular division.

RELATIONS OF CEPHALOPODS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

It has been supposed by some that the shelled cephalopods are and were free-swimming pelagic animals; others have suggested that, although the habits may have been more or less sedentary, after the deaths of the animals their empty shells rose to the surface, where, buoyed up by the air-filled chambers, they floated until these chambers became filled with water.[79] In either case the shells ultimately would come to rest on every type of bottom and hence would mean nothing with respect to the environment in which the owners lived. The latter hypothesis was largely advocated by Walther, and was based on the supposedly world-wide distribution of many species, and in part on his belief that the shells of living species of *Nautilus* and *Spirula* are very much more widely distributed than the animals themselves.

These views of Walther did not gain general acceptance, and in particular they were attacked by Ortmann.[80] Subsequently, Walther[81] explained the extent of his generalization, stating that it was not intended to include all ammonites and that many had very narrow distribution or were confined to very definite sedimentary facies. Such ammonites he considered as having lived in the environment indicated by the sediments. Hyatt[82] was of the opinion that the majority of ammonites crawled on the bottom, that some aberrant species must have been nearly sedentary, and that some forms may have been free-swimming.

The Naples[83] beds of New York contain extremely delicate-shelled ammonites, the shells having little-broken apertures and unimpaired surface ornamentation. Young shells in all stages of development are present, and the conclusion appears inescapable that the sediments represent environments above which the ammonites died. Clarke also points out that the goniatites in the earliest *Styliola* limestones are associated with holo-planktonic organisms and floating logs, implying transportation of the shells into this environment.

Ruedemann[84] from his study of color bands and organisms growing on

[79] Walther, J., Einleitung in die Geologie als historische Wissenschaft, 1894, p. 514.

[80] Ortmann, A. E., An examination of the arguments given by Neumayr for the existence of climatic zones in Jurassic times, Am. Jour. Sci., vol. 1, 1896, pp. 257–270.

[81] Walther, J., Über die Lebensweise fossiler Meeresthiere, Zeits. d. deut. geol. Gesell., vol. 49, 1897, pp. 209–273.

[82] Hyatt, A., Genesis of the Arietidæ, 1889, p. 29.

[83] Clarke, J. M., The Naples Fauna, pt. i, 16th Ann. Rept. of N. Y. State Geologist, 1898, pp. 135 et seq.

[84] Ruedemann, R., Observations on the mode of life of some primitive cephalopods Bull. Geol. Soc. Am., vol. 32, 1921, pp. 315–320.

the shells of some Paleozoic nautiloids concluded that the forms studied (*Orthoceras tenuistriatum* Hall, *O. trusitum* Clarke and Ruedemann, and *Cyrtoceras parvulum* Barrande) must have had crawling habits.

In Stanton's[85] opinion,

> It is reasonable to believe that different species and genera of the ammonites developed habits adapted to all the various life conditions open to them. Their methods of locomotion may have been as different as their shapes. If there were climatic zones in the Mesozoic oceans, there were ammonites adapted to all of them. But whatever species adaptations to conditions there may have been it seems reasonable to believe that most geologists of broad field experience in collecting ammonites from many formations have concluded that the great majority of ammonites lived and died in the neighborhoods in which they are found and that fair inferences concerning the conditions under which they lived may be made from the study of the associated fossils and sediments.[86]

On the other hand, it should not be forgotten that there is much evidence that the dead shells of some species did have a pseudo-planktonic distribution.

Concerning the bathymetric distribution of cephalopods, little is known with respect to those now living, as the life habits of the shelled forms are essentially unknown. More is known of the naked forms, represented by the existing and extinct squids and the extinct *Belemnites*. As these belong to the nekton, however, they have no bearing on depth, and little on bottom environment.

Cephalopods are found in limestones, shales, and sandstones. In some instances the same species has been collected from all three types of sediment. This is not common, and each species occurs in greatest abundance in one type of sediment and is rare in the others.

American examples of limestones rich in nautiloids are the Ordovician, Silurian, and Pennsylvanian limestones of interior North America, and some parts of the Ordovician and Silurian of the St. Lawrence region. Ammonites are common or abundant in the Lower Triassic limestones of Nevada, the Upper Triassic Hosselkus limestone of southern California, the Upper Jurassic limestone near Mazapil, Mexico, and the Cretaceous Austin and Georgetown limestones of Texas. In many instances the associations are with reef-making corals, as in the Hosselkus limestone of California and the Silurian limestones of the Mississippi Valley, Anticosti, and Gotland.

Shales that are notable for their ammonoid faunas include the Jurassic Chi-

[85] Stanton, T. W., The significance of ammonites in interpreting depth and temperature of the waters in which they lived, Manuscript, 1922.

[86] Extensive detail relating to the life habits of the cephalopods is given by Dunbar, C. O., Phases of cephalopod adaptation, in Organic evolution and environment (M. R. Thorpe, ed.), 1924, pp. 187–223.

tina shale of Alaska, the Lower Cretaceous Horsetown shale of California, and the Upper Cretaceous Pierre shale of the Great Plains. Nautiloids are rather common in Silurian and Ordovician shales of Anticosti and in the Silurian of Gotland. As these shales separate limestones and the same species are found in the limestones, it is considered that the latter may represent the real environment, and that the occurrence in the shales was probably brought about by the sudden influx of a large volume of mud which was deposited around the nautiloids lying on the lime bottom.

Sandstones containing nautiloids are not common, but do occur. Ammonites are present in sandstone bands in the Cretaceous Pierre shale of the Great Plains, and the Fox Hills sandstone. The Middle Jurassic Tuxedni sandstone of Alaska, which also includes beds of shale, has a very large and varied ammonite fauna which occurs abundantly in both the sandstone and shale layers, where it is associated with a shallow-water fauna of other mollusks and a few land plants.

The examples cited are interpreted as representing a range of depth from the strand-line to moderate depths of possibly 100 to 200 fathoms. Possibly some of the containing rocks were formed at greater depths, but none seems to have features suggesting great depths. Those containing reef-making corals most certainly must have been formed in very shallow waters.

It thus appears that some cephalopods flourished in the clear-water bottoms essential for limestone formation, whereas other species may have been at home on muddy and sandy bottoms. It is possible that some species ranged freely from one environment to another, although caution is required in making this interpretation for such species as show this distribution, as a sudden inwash of sediment may have killed the animals as well as buried them, and dead shells may have been transported to environments in which their owners could not have lived.

The common association of cephalopods with reefs corals suggests that the former preferred warm waters. The character and distribution of living molluscan faunas of warm waters suggest that ammonites showing luxuriant growth, variety of form and structure, and large sizes, lived in such waters.

It is probable that some extinct cephalopods became adapted to such cold waters as existed, just as *Octopus* and other living cephalopods are found in the North Atlantic and other cold seas. Neumayr[87] used the distribution of certain ammonite genera in connection with other classes of fossils as evidence for the existence of climatic zones during the Jurassic and Cretaceous periods, but as knowledge of these ammonite genera has been

[87] Neumayr, M., Über klimatische Zonen während der Jura und Kreidezeit, Denks. d. k. Akad. Wiss., Wien, vol. 47, 1883, pp. 277–310.

extended it has become increasingly difficult to relate distribution to climatic differences.

RELATIONS OF ARTHROPODS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Trilobites

So far as known, the trilobites were exclusively marine, none ever having been found in deposits of fresh-water origin. They are thought to have been adapted to every marine environment. The following table modified from that of Raymond[88] gives the environments and the trilobite characteristics which are thought to be indicative of each:

Pelagic planktonic: Indicated by vestigial development of the pygidium and the occurrence of spines. *Deiphon*, *Odontopleura*, and *Cyphaspis* are thought to have lived in this environment.

Pelagic nektonic: Indicated by thin shells and large pygidia. Probably a part of the life was spent on the bottom.

Benthonic: Crawlers and poor swimmers with relatively heavy shells and poor pygidia; crawlers and active swimmers with heavy shells and large pygidia; and forms which did a great deal of burrowing as indicated by broad shovel-shaped cephala, pygidia developed for burrowing, and absence or poor development of compound eyes.

The pelagic forms might have become incorporated in any kind of marine or near-marine sediments; the crawlers and swimmers would be more restricted, but their distribution would also be somewhat independent of the environment; burrowers would be likely to be found in fine-grained deposits, and their distribution is in harmony with this generalization. *Trinucleus* and *Triarthrus* are thought to have been burrowers; their tests are most often found in mud deposits. *Calymene* is more often found in sediments which are calcareous or in deposits which are associated with calcareous sediments.

A fact bearing on the distribution of trilobites arises from the periodic moulting of the exoskeleton. These moults were light and had large surface compared to weight, and hence could readily be carried long distances by waters of low competency. They were extremely fragile and easily broken, and the fragments could have attained wide distribution and have become incorporated in sediments which may have borne no relations to the environment in which the trilobites lived. It thus follows that fragments of trilobites throw little light on the environmental conditions within which the owners lived and deserve little consideration as evidence to that effect.

[88] Raymond, P. E., The appendages, anatomy and relationships of trilobites, Mem. Conn. Acad. Arts Sci., vol. 7, 1920, p. 103.

The depths in which the trilobites lived can be determined only from the physical characters of the associated sediments. These indicate shallow water.

Decapods

The decapods live in marine and fresh waters and on land, and their occurrence does not permit a differentiation between the continental and marine environments. In the sea they are mostly confined to shallow waters of less depth than 500 feet; but some species extend to abyssal bottoms. Some are confined to definite environments. Decapods also moult periodically, and the fragmentary remains may therefore become widely distributed. They are rather rare in the geologic column, and their value in determining the environment of deposition is limited.

Planktonic Arthropods

These include the phyllopods, copepods, and ostracods. As they belong to the plankton, their distribution at all times has been independent of the character of the bottom, and they lend little to evaluation of conditions of the environment.

Barnacles

Barnacles belong either to the sedentary benthos or the epiplankton and epinecton. They live in both cold and warm water. The acorn barnacles, *Balanus*, are mostly benthonic and confined to shallow water, but extend to depths of 3,000 feet. The goose barnacles, *Lepadidæ*, are either epinectonic and epiplanktonic, living attached to fishes, whales, and floating objects; or benthonic, and the latter in their distribution extend to abyssal depths. The parts of the shell are likely to separate after death. Shells are not very common in the geologic column. Shells of acorn barnacles suggest shallow water, but for their occurrence to mean very much the shells should be abundant and still attached.

Merostomata

The Merostomata include the modern *Limulus* and related fossil forms, the eurypterids, and certain other early Paleozoic types. *Limulus* belongs to the vagrant benthos and lives in shallow marine waters. It is often found partly buried in mud, and at the present time it is restricted to the eastern shores of America and Asia. It seems certain that the ancestors and ancient closely related forms of *Limulus* were mostly non-marine, as a Tertiary species is known from the Oligocene brown coal of Saxony, and the Carboniferous forms, *Prestwichia* and *Belinurus*, are associated with the

Coal Measures in a way which essentially proves a fresh-water habitat. *Cyclus*, another Carboniferous form, is found in both marine and fresh-water deposits, possibly attaining the former through being carried to sea by streams.

The eurypterids may have lived mostly in fresh waters, although it is not proved that some were not marine. Miss O'Connell[89] has studied and correlated all the data bearing on the habitat of eurypterids and has reached the conclusion that they lived in fresh water. The specimens which have been found in marine deposits may be interpreted as having been brought to the sea by streams, as the exoskeletons must have floated very readily in currents of low competency. The Limulava from the Cambrian appear to have been marine forms, as they occur in association with an abundance of marine fossils.

The occurrence of any of the Merostomata strongly suggests a shallow-water environment, and, unless the evidence is strongly to the contrary, that of fresh waters. The known distribution is markedly discontinuous, both for living and extinct species.

Spiders, Insects, and Myriopods

These groups give little evidence that permits an evaluation of the sedimentary conditions. Dwarfed forms of insects are thought to suggest low temperatures, but it is by no means certain that such is the case.

RELATIONS OF WORMS TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

Worms live in marine and fresh waters and on the land. The forms living in the water belong mostly to the benthos; a few are planktonic or nectonic. They live on all kinds of bottoms and to great depths, living in mud, sand, and in tubes of their own making which may be attached to any solid object. Species are difficult of determination, and occurrences of their tubes, borings, and trails throw little light on environmental conditions.

RELATIONS OF VERTEBRATES TO SEDIMENTS AND SEDIMENTARY ENVIRONMENTS

BY W. D. MATTHEW[90]

Two kinds of evidence are provided by extinct vertebrate animals of the environment in which they lived:

[89] O'Connell, M., The habitat of the Eurypterida, Bull. Buffalo Soc. Nat. Sci., vol. 11, no. 3, 1926.

[90] The manuscript for this topic was prepared for the first edition by Doctor Matthew. His death in 1930 precluded his making any revision and, except for an occasional change of wording, there has been no modification.

1. Skeletal characters directly indicating adaptations in the animal to special food, habitat, or mode of life that is more or less dependent on a particular type of environment.

2. Near relationship to existing animals of more or less restricted environment.

The first line of evidence involves study of the fossil skeleton as an adaptive mechanism and a reconstruction of the animal, with working hypotheses of the purpose of the various structures of its organism. The second is supplementary evidence, and, except so far as it is supported by the first, is less trustworthy, as the present restrictions of environment may not always have been the same.

Certain broad lines of adaptation are obvious enough. The legs and feet of terrestrial vertebrates, paddles or fins in purely aquatic types, wings in aerial forms, are easily recognized in the skeleton. Readaptation frequently makes use of specializations designed for one mode of life, modifying them to suit another. These new adaptive characters must be correctly distinguished from the older adaptive characters of the animal, if its true adaptation is to be interpreted.

Vertebrates have a wider range of movement than most invertebrates or plants. Nevertheless, they are rarely found at any great distance from their normal habitat. Those restricted to a life habitat outside the range of sedimentary deposition are rare or unknown as fossils. Among aquatic vertebrates fish are naturally most abundant. Swift-swimming pelagic types of fish, reptiles, and mammals have a characteristic spindle-formed body, wide forked tail, and are exclusively marine. Such are the ichthyosaurs, mosasaurs, nearly all cetaceans, certain groups of Mesozoic crocodiles, and many families of fishes. The shorter, plumper fishes occur both in marine and fresh water. Plesiosaurs are almost wholly marine, but fossil specimens have been found in fresh-water formations. The slender-muzzled crocodiles of the Mesozoic are marine so far as known, but their modern analogues, the gavials, are of estuarine habitat. The broad-nosed crocodiles, on the other hand, are all fresh-water dwellers. Champsosaurs, analogous in structure to the gavials, are estuarine. The Chelonia range from purely marine to purely terrestrial types. Their several families are distinguished by adaptive specializations in the skeleton which, for the most part, clearly show their habitat and conform with the habitat of the existing species in each group. The Protostegid and Toxocheliid families of the Mesozoic and the sea-turtles of the present day are strictly pelagic, with highly specialized flippers. Other groups, with flippers and heavy crushing teeth, are of littoral habits; the Trionycids are aquatic fresh-water types with flipper-like feet; the Emydids and Dermatemydids, with feet adapted

to walking but webbed to a varying degree, range from largely aquatic to wholly terrestrial. True tortoises have feet adapted to walking on dry land and are strictly terrestrial.

Fossil birds are so rare as to be almost negligible as evidence for environment, and mammals provide the bulk of environmental evidence for most terrestrial faunas.

The skeleton affords direct evidences of specialization for tree-living, burrowing, amphibious or swimming, or cursorial habits; these are seen especially in the limbs and feet, but also in other parts of the skeleton. In a heavily wooded region a large proportion of the animals will be more or less arboreal; swift-running types will be rare or absent, because in the forest it is agility and not speed that conduces to survival. Streams and lakes are relatively large and frequent, and amphibious or aquatic animals fairly common. Fossorial types, on the other hand, are rare in such an environment, for protection is easily secured without digging in. On the other hand, in an open country with the streams few and small, trees limited to the stream borders, and no continuous woodland but wide grassy plains, the cursorial mammals will be abundant, tree-dwelling types will be scarce or absent, and fossorial specializations will be common, especially among the smaller forms. Aquatic or amphibious animals may still haunt the larger streams, and their remains are more apt to be found as fossils, but they tend to be limited to stream channels and absent from the finer flood-plain sediments.

The prevalence of grassy open country brings corresponding adaptations in the teeth. In the forest, leaves and twigs, roots and tubers, and various fruits and nuts are the available food supply; browsing, frugivorous, and omnivorous adaptations prevail throughout the fauna. Abundance of grasses introduces a new specialization, the grazing type, with long-crowned teeth adapted to this type of food. The browsing and other types do not disappear, for they can still maintain themselves on the stream-band vegetation, but grazing types appear in larger proportion as the country becomes more open and the forest disappears.

The more extreme semi-desert environment involves a great scarcity of water, so that animals must travel long distances to the occasional drinking pools, chiefly in the beds of temporary streams. As such streams are important centers of deposition and their pools the vortices of animal life, records are chiefly limited to them, presenting what is probably a very imperfect picture of the life of the district as a whole. Only those animals which either live around the pools or resort to them for drinking are likely to be caught and preserved as fossils. In the loess or desert sands, formed away from streams, fossil vertebrates are relatively rare.

Little or nothing is known of the highland and mountain life contemporary with that of the valleys and lowlands, and our vertebrate faunal record is chiefly of the life of the valleys, flood plains, and river deltas, giving no direct light on the upland or mountain faunas. One or two possible exceptions, such as the Solenhofen land fauna, serve rather to emphasize the extent of our ignorance by diversity from the normal vertebrate faunas of the time.

Probably the most largely used, but not the most dependable, of environmental evidence turns upon the habitat and climatic adaptation of existing relatives of the animals considered. The early discoveries of fossil elephants, rhinoceroses, hippopotami, lions, hyenas, and other tropical animals in the Pleistocene were taken to indicate a tropical climate in the north at that time. But this evidence has been gravely discredited by the discovery that certain of these animals were especially equipped to withstand an arctic climate and by their frequent discovery in the frozen tundra of the far north. Somewhat more weight is to be attached to the discovery of arctic animals far to the south of their present range. Such evidence, however, unless it is conformant throughout the fauna, or supported by direct evidence of climatic adaptation and limitation, is far from conclusive even when the relationship to modern types is very close. The tapirs of the New Jersey and Pennsylvania Pleistocene are closely related to modern species of tropical America and afford some indication of an interglacial climate warmer than now; the peccaries, belonging to extinct genera, have no serious weight, and there is good reason to believe that they were adapted to a much more northerly climate than their living relatives, for they are not found associated with tapirs, but do occur in faunas that include the wolverine, musk-ox, caribou, and other northern animals. On the other hand, the northern range of crocodiles is limited by their physical inability to adapt themselves to a cold winter climate. Their occurrence in the Oligocene and Miocene of South Dakota and Nebraska affords conclusive proof that the winters there were not as cold then as now. The habits of the hippopotamus are hardly reconcilable with a prolonged season of frozen streams, and although it is possible that the animal was merely a summer visitor, the explanation seems far-fetched.

Each instance of vertebrate remains must be separately and critically weighed, and data which appear to be conflicting must be fully reconciled before any conclusions can safely be drawn as to environmental conditions.

CHAPTER V

PRODUCTS OF SEDIMENTATION

General Considerations

Each sedimentary product is a consequence of an environment, and each environment is due to the combination of certain chemical, physical, and biological factors. The number of these factors is very great, and changes in any one are likely to modify several others, with consequent changes in the characters of the sediments deposited. Thus, each product is due to a delicate adjustment of all the controlling factors. It is inevitable that environments pass laterally into others which are to some degree different, and the differences may be extreme.

The various substances transported and deposited are more or less sorted, but as sorting is done on several bases and is never or rarely perfect on any, chances are slight that a mechanical deposit will be composed of a single substance of the same physical characteristics throughout. The consequences are that there are all gradations between every variety of sedimentary product and all others. Thus, calcite limestones grade into magnesian limestones and dolomites, cherts, sandstones, shales, and essentially every other variety of sedimentary product. Coal shows similar gradations, and likewise all others. This makes classification difficult and any dividing lines erected must be purely arbitrary.

A convenient method of classification which has been more or less used is based on the character of the agents of deposition. Thus, sediments are classified as of mechanical and chemical origin, the latter division subdivided into organic and inorganic. This classification is difficult of application, as many of the sedimentary deposits, and probably most of them, have both mechanical and chemical constituents, but it is considered no more difficult than any other, and it is used in this work. Grabau[1] has proposed an elaborate scheme of classification, with a great number of new terms, which endeavors in the terminology used to express to some extent the chemical constitution of the product and also the environment in which it developed. The scheme merits consideration, but it is doubtful if it will come into extensive use. It is not believed that the study of sediments is sufficiently advanced for the preparation of a detailed classification.

[1] Grabau, A. W., Principles of stratigraphy, 1913.

Mechanical sediments include such rocks as sandstone, conglomerate, and shale; the so-called chemical sediments are most of the limestones, coals, cherts or flints, gypsums, some of the iron-bearing sediments, some silicates, and others. Some substances are carried in the colloidal state and precipitated by electrolytes in solution or other colloids, the resulting products being difficult to classify. Calcite, iron oxides, and substances derived from pre-existing rocks are deposited by mechanical agencies. After these are consolidated their differentiation is difficult from the very similar products precipitated directly by chemical processes.

On the basis employed, sedimentary products are grouped as follows:

Products resulting from mechanical deposition

A. The coarser-grained clastics: sands, gravels, boulders, etc.; and their indurated equivalents: sandstones, conglomerates, etc.
B. The finer-grained clastics: clays and silts, and their indurated equivalents: shales.

Products resulting from chemical deposition

A. Products dominantly calcareous: various oozes and shell accumulations; and their indurated equivalents: limestones and dolomites.
B. Products dominantly siliceous: chert, flint, and various silicates.
C. Products dominantly ferruginous: limonite, hematite, glauconite, pyrite, etc.
D. Products dominantly carbonaceous and bituminous: coal, oil shales, etc.
E. Miscellaneous: gypsum, rock salt, etc.

In the discussion of these various products there is little attempt to be consistent. Thus, in discussing the iron-bearing sediments, mechanically precipitated and transported magnetite is considered in connection with the other ferruginous sediments; glauconite, of which the major constituent is silicon dioxide, is considered in the same connection. Many substances of minor importance are not discussed, although locally they enter largely into sedimentary units.

The study of any sediment involves examination with respect to properties, characteristics, and origin. The problem of origin necessitates a consideration of the sources of the sediment, the agents responsible for transportation to the places of deposition, the processes responsible for deposition, and the environment in which the last occurred.

The different varieties of sediments succeed each other in an extremely variable arrangement. Thus, any particular variety of sediment may succeed sandstone, shale, coal, rock salt, limestone, etc., the variations being like those existing in lateral distribution, but as a rule more abrupt. These vertical or sequential changes in the variety of sediments reflect changes in the environment, but it must not be assumed that the environmental

changes were as abrupt as the sediments imply, as the separating bedding planes between different varieties of sediments in many cases represent times of no deposition. The sequence of sediments and other rocks of any place form the geologic column of the place, the geogram of Marr.[2] The area of the place concerned is limited only by the area of the earth.

The Minerals of Sediments

The study of the minerals of sediments has received the attention of European students for many years and the results of their research embellish many pages of scientific journals, reports, and books. Pioneers in this work are Bonney, Cayeux, Collet, Lacroix, Mackie, Murray, Sorby, and Thomas. Other Europeans who have made notable contributions are Anten, Boswell, Brammal, Chelussi, Clerici, Deverin, Davies, Doyen, Fleet, Gilligan, Groves, Holmes, Milner, Rastall, Shannon, Versey, Wetzel, and others. Most of the work of the later contributors, among whom Boswell, Holmes, Hatch, Milner, and Rastall are particularly noteworthy, was published after 1915. The leader in petrographic study of sediments in America seems to have been Goldman, whose work on the Cretaceous sediments of Maryland was published in 1916. Among other American students whose work has been important are Edson, Reed, and Ross.[3]

The occurrence and characteristics of the minerals of sediments are of great importance in connection with several ramifications of geology. The minerals aid in correlation; they assist in unraveling ancient geography in that they suggest the sites of distributive provinces and the places undergoing erosion; they give data on the methods of transportation and thus the directions of the rivers and the other agents of transportation; their identities and the characters developed in transportation assist in the determination of ancient climates; they aid in working out the geologic history of a region by showing what rocks were at the surface to make contributions in the form of sediments; and they assist in exploration and development of geologic resources.

Correlation of strata with the assistance of minerals is more secure than if based on fossils alone, and for strata without fossils the minerals and their

[2] Marr, J. E., Classification of sedimentary rocks, Quart. Jour. Geol. Soc., vol. 61, 1905, p. lxii. See also Watts, W. W., Geology as geographical evolution, Ibid., vol. 67, 1911, pp. lxii–xciii.

[3] Reference is made to some of the important papers on succeeding pages. Milner in the revised edition of his "Sedimentary Petrography" gives an excellent bibliography and to this the reader is referred. The reader should also consult the reviews with bibliography published from time to time by Professor Boswell, those published to date are Proc. Liverpool Geol. Soc., vol. 14, 1923, pp. 231–303; vol. 14, 1924, pp. 1–33; vol. 14, 1925, pp. 164–180; vol. 14, 1927, pp. 319–339.

assemblages may be the only means of correlation. Fossils too frequently are absent or are too poorly preserved for use; minerals are always present and the cases seem few where they are not distinctive and excellently preserved. The following table from Milner[4] illustrates how mineral assemblages occur in sedimentary sequences:

Horizon	Mineral assemblages
Bagshot Sand	Abundant ilmenite and zircon; large and complexly cleaved kyanites, deep red rutile in excess of yellow variety; subordinate staurolite and hornblende; general absence of garnet.
London Clay	Noteworthy abundance of muscovite; presence of garnet; yellow anatase not uncommon; epidote distinctive; frequent gypsum and pyrite; limonite, kyanite, and zircon nearly always present.
Blackheath Beds	Essentially a tourmaline, staurolite, zircon, and kyanite assemblage; garnet present; andalusite scarce, but usually persistent; ilmenite always in excess of magnetite.
Woolwich Beds	Somewhat similar assemblage to that of the Blackheath Beds; strong influx of rutile; biotite and apatite not uncommon; garnet usually scarce.
Tanet Sand	Very different type of assemblage from the Woolwich Beds; ilmenite abundant; staurolite and zircon very common; rutile, tourmaline, and garnet distinctive; limonite, epidote, and kyanite always present; noteworthy increase of glauconite (in light samples) compared with younger deposits.
Chalk	Always presents a very restricted residue, zircon, tourmaline, staurolite, and ilmenite being the usual species; pyrolusite local and more restricted in the upper horizons.
Upper Greensand	Glauconitic casts of foraminifera in light portions of sample very common, and distinctive black and white mica both common; garnet, calcite, and irregular zircon and epidote present.
Lower Greensand	Very rich residue; ilmenite, vari-colored tourmaline, deep yellowish-brown staurolite; distinctive kyanite; rare andalusite; rutile common; epidote characteristic of upper horizons; sphene, apatite, and barite noted; also zinc-blende locally; limonite and glauconite common; tendency for garnet to be absent or very rare.

By means of mineral assemblages Milner has been able to distinguish[5] all of the horizons of the Lower Cretaceous Wealden series, and the detailed mineral stratigraphy has served to unravel the structural complexities of the region of occurrence. Reed[6] has been equally successful in the Tertiary

[4] Milner, H. B., The study and correlation of sediments by petrographic methods, Mining Mag., vol. 28, 1923, p. 85.

[5] Milner, H. B., Proc. Geologists' Assoc., vol. 33, 1922, pp. 141–145; vol. 34, 1924, pp. 47–55.

[6] Reed, R. D., Rôle of heavy minerals in the Coalinga Tertiary formations, Econ. Geol., vol. 19, 1924, pp. 730–749.

of the Coalinga region of California and also near the Lost Hills region in the upper end of the San Joaquin Valley of that state.[7]

Minerals may also be used to arrange the strata of a formation into zones just as fossils are used to the same end, each zone being characterized qualitatively by minerals of a certain kind or a certain assemblage, by minerals having certain distinctive characteristics, by the appearance of new minerals or the dropping out of old; or quantitatively by the percentages of the total heavy minerals or certain of the heavy minerals, the average dimensions of the mineral particles, or the assortment of the particles as shown by graphs of their fractions. Zoning is difficultly done in cases where the beds are lenticles of limited extent and it can not be done at all in strata that have vertical homogeneity. Study of samples acquired in drilling into unexposed strata will readily demonstrate regularity or lenticularity of deposits. Even in lenticular strata, however, it is quite possible that zoning may be excellently done.

However, too much reliance must not be placed on the mineral content of strata, as horizons in the same section may have similar minerals and similar assemblages. Likewise, in sections which show much lateral and vertical variation the mineral assemblages may have little significance, the cause resting on the nature of the depositing agents and the possibility of derivation of sediments from many terranes within a limited area. Lithic units of extensive persistence indicate a constancy and a greater spreading ability of the depositing agents, and such units are likely to have a greater persistence of mineral character and assemblage. This is shown by the Jordan-Madison sandstone unit of the Upper Cambrian of the upper Mississippi Valley, which has a quite similar mineral assemblage over the entire region of outcrop. Strata of the same identical age, but within different basins of deposition and even different parts of the same basin, may be expected to have different mineral assemblages.[8] Reed and Bailey have expressed the opinion that correlation of zones by means of heavy minerals would not ordinarily be dependable over distances of many miles, at least not unless samples were available at intervening points, but that conditions do obtain in California where some formations seem to be separable on the basis of heavy minerals over distances as great as 200 miles.

In unraveling ancient geography and determining the provenance and distributive provinces of sediments and the directions of the streams and

[7] Reed, R. D., and Bailey, J. P., Subsurface correlation by means of heavy minerals, Bull. Am. Assoc. Pet. Geol., vol. 11, 1927, pp. 360–368.

[8] Milner, H. B., Quart. Jour. Geol. Soc., vol. 78, 1922, pp. 344–377; also Sedimentary petrography, 1929.

currents, the abundance, identities, and assemblages of minerals afford an excellent aid. Cayeux[9] states that it is known from the distribution of the mineral particles that currents from the north and south entered the Cretaceous sea over the Paris Basin, the current from the south bringing the mineral kyanite whose occurrences show the distribution of the transporting currents. A brilliant piece of research in the determination of source rocks of sediments is that of Mackie in tracing the purple zircons in the British sediments to the Lewisian gneiss.[10] The work of Gilligan[11] on the Millstone Grit, in which he showed that its materials came from the north, is excellent, and in the same class is the work of Heard and Davies[12] on the Old Red Sandstone of the Cardiff District, in which a northern source for the sediments was indicated. Brammall's[13] work and that of Groves[14] on the detritals from the Dartmoor granite are outstanding illustrations of what may be done with heavy minerals in deciphering ancient geography. Bearing on ancient geography is also the work of British students on the Pebble Beds and other sediments of the Bunter sandstone,[15] in which Scottish, Armorican, or Devon-Cornwall sources were postulated.

Determination of the sources of the materials found in sedimentary rocks requires a knowledge of the minerals in the rocks of the possible sources. This is not often realized. Research, however, should not be discouraged and should not fail to determine the minerals in the sedimentary rocks, as these additions to knowledge will permit interpretations in the future when the accessory minerals of the igneous rocks have been learned. The ideal procedure would be contemporaneous and parallel studies of the source

[9] Cayeux, L., Introduction à l'étude pétrographique des roches sédimentaires, 1916, p. 47.

[10] Mackie, W., The source of the purple zircons in the sedimentary rocks of Scotland, Trans. Edinburgh Geol. Soc., vol. 11, 1923, pp. 200–213.

[11] Gilligan, A., The petrography of the Millstone Grit of Yorkshire, Quart. Jour. Geol. Soc., vol. 75, 1919, pp. 251–294.

[12] Heard, A., and Davies, R., Old Red Sandstone, Cardiff District, Quart. Jour. Geol. Soc., vol. 80, 1924, pp. 489–519.

[13] Brammall, A., Dartmoor detritals; a study of provenance, Proc. Geologists' Assoc., vol. 39, 1928, pp. 27–48.

[14] Groves, A. W., The unroofing of the Dartmoor granite and the distribution of its detritus in the sediments of southern England, Quart. Jour. Geol. Soc., vol. 87, 1931, pp. 62–96.

[15] Bonney, T. G., The Bunter Pebble-beds of the Midlands and the sources of their materials, Quart. Jour. Geol. Soc., vol. 56, 1900, pp. 287–306; Burton, T. H., The microscopic material of the Bunter Pebble-beds of Nottinghamshire and its probable source of origin, Ibid., vol. 74, 1918, pp. 328–339; Thomas, H. H., A contribution to the petrography of the New Red Sandstone of the west of England, Ibid., vol. 58, 1902; Shrubsole, O. A., On the probable source of some of the pebbles of the Triassic beds of South Devon and the Midland counties, Ibid., vol. 59, 1903, pp. 311–333.

rocks and the sediments derived from them, as was done by Smithson[16] in the Dublin District of Ireland.

The characteristics of mineral particles may indicate the method of transportation from the sources to the sites of deposition, and may show the entrance of materials from different sources and by different methods of transportation. Small grains with high sphericity and with mat surfaces suggest eolian transportation. Subangular grains with polished surfaces suggest the deposits of running water. Poorly rounded grains of mixed identities suggest fluvial transportation, and angular grains of mixed identities may be correlated with the deposits of piedmont regions or those of glaciers. As noted on other pages, however, too much weight must not be placed on these characteristics, as particles may be deposited in an aqueous environment whose major transportation was accomplished by eolian agencies, and any agent of transportation may acquire materials from the deposits of any environment. Nevertheless, the assortment and the sedimentary structures, taken in connection with the physical characters of the minerals and their identities, should generally serve to indicate the method of transport. The appearance of the same mineral with different transportation effects should usually be interpreted as denoting contributions from two sources. This is illustrated by the presence of brown and blue tourmalines in the Triassic rocks of the Wirral Peninsula near Liverpool on the west coast of England. The brown tourmaline is much worn and long transportation is indicated and a probable distant source; the blue is little worn, indicating little transportation and a source close at hand.[17]

The species of minerals, the composition of their assemblages, and some of their physical characters may permit determinations of whether the immediate source rocks are igneous, metamorphic, or sedimentary. If igneous, the mineral assemblages would indicate such by a wide variety of stable and meta-stable accessory minerals of igneous rocks, and these would not have the impress of metamorphic action. If the source terrane is metamorphic, the minerals should show effects of pressure in the occurrence of elongation, mashing, strain shadows, etc. Sedimentary terranes contribute original materials of igneous rocks from which the meta-stable minerals have largely been eliminated and only the more stable remain. Climatic and other factors may, however, modify the results, so that caution is essential. The

[16] Smithson, F., Geological studies in the Dublin District. I. The heavy minerals of the granite and contiguous rocks in the Ballycorus District, Geol. Mag., vol. 65, 1927, pp. 12–25.

[17] Travis, C. B., and Greenwood, H. W., The mineralogical and chemical constitution of the Triassic rocks of Wirral, Proc. Liverpool Geol. Soc., vol. 11, 1911, pp. 116–139.

work of Ockerman[18] and Pentland[19] has shown that the materials of the Madison-Jordan and Franconia-Mazomanie Upper Cambrian formations were probably derived from sedimentary terranes, and Workman has presented the evidence that the Permian sandstones of the Parbold District of England derived their materials from the Millstone Grit of the same region.[20]

The determination of something of the geologic history of a region may be made from the minerals in sediments. Until a formation is exposed at the surface, particles therefrom can not enter into deposits. Thus, the first appearance of particles of a given character denotes appearance of the source rock at the surface at an elevation sufficient to supply the particles. In this way diastrophism, vulcanism, or the uncovering of a terrane may be dated. Reed,[21] for example, has shown from the occurrence of glaucophane that the Jurassic Franciscan rocks were undergoing erosion in Temblor time (Lower Miocene), whereas previously it had not been known that the Franciscan had supplied sediments prior to the Upper Miocene. The minerals of the Kreyenhagen formation (Oligocene?) indicate that the Franciscan was not exposed at that time. Similarly Greenly[22] has shown that in Anglesey, Wales, the old rocks of the region, known as the Mono Complex, were not exposed after the deposition of the basal conglomerate of the Old Red Sandstone. The materials of the basal conglomerate were largely derived from the Mono Complex, whereas the minerals of the overlying finer sediments bear little relation to those of the Mono Complex, indicating that after the deposition of the basal conglomerate the old rocks were no longer in a position to supply sediments to the Anglesey Old Red Sandstone basin of deposition, the interpretation being that the Mono Complex terrane had become covered with sediments and thus was unable to contribute to the deposition of the finer materials. Mackie has shown from the contents of the Torridon sandstones that the Moine schists are older than the Torridon.[23] Groves's work on the detritals of the Dartmoor

[18] Ockerman, J. W., A petrographic study of the Madison and Jordan sandstones of southern Wisconsin, Jour. Geol., vol. 38, 1930, pp. 346–352.

[19] Pentland, A., The heavy minerals of the Franconia and Mazomanie sandstones, Jour. Sed. Pet., vol. 1, 1931, pp. 23–26.

[20] Workman, M., The petrology of the Permian sandstones of the Parbold District, Proc. Liverpool Geol. Soc., vol. 13, 1923, pp. 308–322.

[21] Reed, R. D., Rôle of heavy minerals in the Coalinga Tertiary formations, Econ. Geol., vol. 19, 1924, p. 731.

[22] Greenly, E., The sources of the Old Red Sandstone of Anglesey, Proc. Liverpool Geol. Soc., vol. 14, pt. iv, 1927, pp. 343–350.

[23] Mackie, W., The heavy minerals in the Torridon sandstones and metamorphic rocks of Scotland, and their bearing on the relative ages of those rocks, Trans. Edinburgh Geol. Soc., vol. 12, pt. i, 1928, pp. 181–182; Geol. Mag., vol. 64, 1927, pp. 141–142. Paper read Nov. 17, 1926.

granite has shown that it probably was first unroofed toward the end of the Weald. This field of sedimentary petrography is one of much promise.

Climate is suggested by the varieties of minerals present and also to some extent by the physical characters of the particles. In the destruction of rocks to produce sediments, it is obvious that survival is determined by physical and chemical stability under the conditions of destruction.[24] The sedimentary rock resulting from accumulation of particles derived from igneous rocks may in turn be destroyed, and in the destruction some additional minerals are likely to be eliminated, hence the number surviving would be less than in the first case. These second sedimentary rocks might be destroyed, with additional minerals disappearing. Minerals not surviving the second destruction may be designated one-cycle, those not surviving the third two-cycle, etc. These designations must not, however, be taken too seriously, as the environmental factors may be of such character as to permit many minerals to survive under one environment which would be eliminated under another. Each mineral is likely to become smaller as it progresses from one cycle to another.

In regions where the conditions favor mature decomposition, only the most chemically stable minerals escape the agents of destruction, the ferro-magnesian minerals, the feldspars, and other unstable or little stable minerals breaking down to form other substances which are in harmony with the environment. Under conditions favoring immature decomposition many unstable and moderately stable minerals would be likely to survive and become incorporated in deposits. The conditions favorable to immature decomposition are dry and cold climates, and topography of considerable slope. An abundance of feldspar is usually interpreted as indicative of immaturity of decomposition and suggestive of dry conditions.[25] It must not be considered, however, that the absence of unstable and little stable minerals precludes the occurrence of cold or dry climates and proves the existence of climatic conditions leading to the elimination of the little resistant minerals, as it may be that the source rocks did not contain such minerals. Also, an abundance of unstable minerals does not prove that the climatic conditions were not those favoring mature decomposition, as the topographic and other conditions may been have such as to facilitate rapid removal. The general premise that an abundance of ferro-magnesian minerals and

[24] Mackie, W., The principles that regulate the distribution of particles of heavy minerals in sedimentary rocks, as illustrated by the sandstones of north-east Scotland, Trans. Edinburgh Geol. Soc., vol. 11, 1923, pp. 231–303; Boswell, P. G. H., Some aspects of the petrology of sedimentary rocks, Proc. Liverpool Geol. Soc., vol. 13, 1923, pp. 138–164.

[25] Mackie, W., The feldspars present in sedimentary rocks as indicators of the existence of contemporary climate, Trans. Edinburgh Geol. Soc., vol. 7, 1889, pp. 443–468; Barton, D. C., The geologic significance of arkose deposits, Jour. Geol., vol. 24, 1916, pp. 417–430.

feldspars suggests inhibition of decomposing conditions, and the absence of such minerals, decomposing conditions, is valid, but certain factors may modify the results and these must never be forgotten.[26]

Studies of the distribution of minerals in alluvial deposits of a drainage system may direct an exploring geologist to better placers present in these

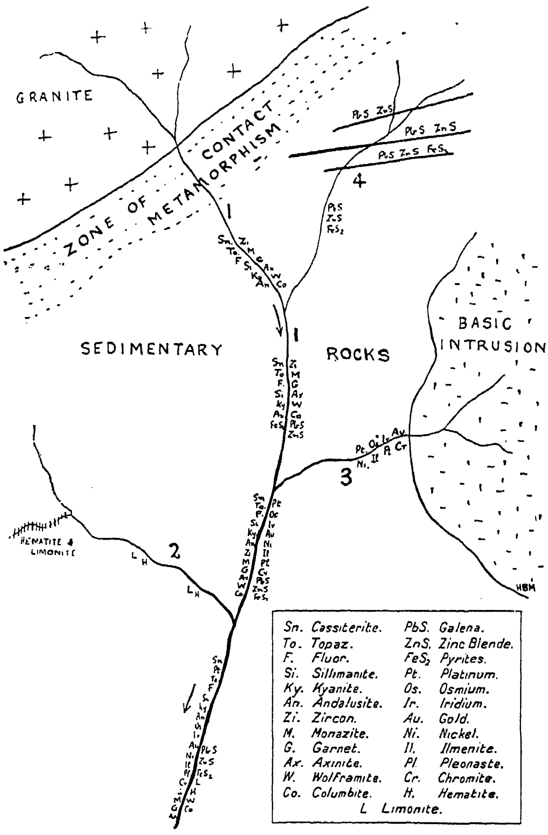

FIG. 13. DIAGRAM SHOWING DISTRIBUTION OF MINERALS IN AN ALLUVIAL DEPOSIT AND RELATIONS OF THE MINERALS TO DISTRIBUTIVE AREAS
After H. B. Milner

deposits. The ultimate sources of the minerals in the deposits might also be found. Figure 13 from Milner shows the applications in this field.[27]

[26] Reed, R. D., Rôle of heavy minerals in the Coalinga Tertiary formations, Econ. Geol., vol. 19, 1924, pp. 737–739; The occurrence of feldspar in California sandstones, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 1023–1024.

[27] Milner, H. B., The study and correlation of sediments by petrographic methods, Mining Mag., vol. 28, 1923, p. 80-92.

Greenwood and other counties of Kansas and Oklahoma contain oil pools which seem to be confined to the fillings of ancient stream channels. Careful studies of the petrography of these channel fillings might result in tracing to their sources the sands which form the fillings, and results of commercial importance might be acquired.[28]

Subsurface correlation through studies of drill samples has made possible the determination and location of structure concealed on the surface. Until recent years such work has been largely confined to organizations and geologists concerned with metal mining, but during the past decade and a half this application of sedimentary petrography has received tremendous impetus through the work of petroleum companies. Many companies maintain staffs to do core drilling for location of structure concealed beneath unconformities or not determinable from surface exposures, and there are several organizations in the Mid-Continent region which have such exploration as their chief objective.[29]

The minerals of sediments may be placed in two classes, detrital or allothogenic and authigenic. The detrital minerals may be any of those occurring in the earth's crust, but only the most stable of the common minerals are likely to occur in any abundance. The authigenic minerals, or those which develop through sedimentary processes, may, in some cases, compose nearly the whole of a deposit, or they may be present in occasional particles. Such authigenic minerals as calcite, dolomite, anhydrite, gypsum, halite, quartz, and hematite and limonite may compose beds of great extent and thickness.

The common detrital minerals are given by Milner as follows.[30]

x	anatase	c*	t	chlorite	c
y	andalusite	l	x	chromite	r
z	apatite	r	x	columbite	vr
y	augite	l	z	cordierite	l
x	barite	r	x	corundum	l
y	biotite	l	x	diamond	vr
x	brookite	c	y	epidote	c or A
t	calcite	l or A	x	fluorite	l
x	cassiterite	l	x	garnet	c
x	chalcedony	c	z	glauconite	c

* x, stable; y, moderately stable; z, unstable; c, common; l, local; r, rare; A, alteration product; vr, very rare; t, stable as secondary product.

[28] Rich, J. L., Shoestring sands of eastern Kansas, Bull. Am. Assoc. Pet. Geol., vol. 7, 1923, pp. 103–113; Buried Pennsylvanian channels and sandbars of eastern Kansas, Abstract, Bull. Geol. Soc. Am., vol. 37, 1926, p. 159; Further observations on shoestring oil pools of eastern Kansas, Bull. Am. Assoc. Pet. Geol., vol. 10, 1926, pp. 568–580.

[29] Reed, R. D., and Bailey, J. P., op. cit.; Trowbridge, A. C., and Mortimore, M. E., Econ. Geol., vol. 20, 1925, pp. 409–423.

[30] Milner, H. B., Mining Mag., vol. 28, 1923, pp. 80–92.

z	glaucophane	r	x	orthoclase	c
x	gold	vr	x	plagioclase	c
y	gypsum	l or A	z	pyrites	c
t	hematite	A	y	pyrolusite	r
y	hornblende	r	z	pyrrhotite	l
y	hypersthene	r	z	quartz	c
y	ilmenite	c	x	rutile	c
t	kaolinite	A	t	siderite	or A
x	kyanite	c	x	sillimanite	l
x	leucoxene	c	x	sphene	r
t	limonite	A	x	spinel	r
x	magnetite	c	x	staurolite	c
y	marcasite	l	x	topaz	c
x	microcline	l	x	tourmaline	c
x	monazite	r	x	wolframite	l
x	muscovite	c	x	xenotime	vr
z	olivine	r	x	zircon	c

To the above list may be added actinolite, benitoite, crossite, dumortierite, diopside, lawsonite, moissanite,[31] piedmontite, spodumene, tremolite, uvarovite, and zoisite, these being common in the California Tertiary and no doubt elsewhere. Dolomite should also be added, as it is a common detrital in some of the beach sands about the Mingan Islands in the Gulf of St. Lawrence, and it seems desirable that there should be included certain varieties of rocks like flint and chert, since there are places where particles of these form large parts of the detritals. Reed and Bailey,[32] and Reed[33] have found particles of amphibolites particularly useful in the Tertiary of California. Such minerals as kaolinite, hematite, limonite, siderite, gypsum, pyrite, calcite and glauconite aid little in attaining any of the objectives given on earlier pages. Minerals designated as stable might be expected to survive several cycles, but there are many factors to modify the results.

The important authigenic minerals of sediments are:

Anhydrite	a	Feldspar	r	Phosphates	c
Aragonite	c	Galena	c	Pyrite	c
Azurite	r	Glauconite	a	Quartz	a
Barite	r	Greenalite	r	Rutile	r
Brookite	r	Gypsum	a	Siderite	c
Calcite	a	Halite	a	Sphalerite	r
Celestite	r	Hematite	a	Strontianite	r
Chalcedony	c	Leucoxene	r	Sulphur	r
Chamosite	c	Limonite	a	Witherite	r
Clay min.	a	Malachite	r	Zeolites	r
Dolomite	a	Manganese min'ls	c		

[31] Ohrenschall, R. D., and Milton, C., The occurrence of moissanite in sediments, Jour. Sed. Pet., vol. 1, 1931, pp. 96–99.

[32] Reed, R. D., and Bailey, J. P., op. cit.

[33] Reed, R. D., Rept., Comm. Sed., Nat. Research Council, 1927, pp. 77–78.

The different minerals are described in detail in works on sedimentary petrography, to which the reader is referred. Standard works are given below.[34]

The minerals occurring in sedimentary rocks are divided into heavy and light. Minerals of which the specific gravities exceed 2.90 belong to the heavy division, as these sink in the so-called heavy liquids, like bromoform and tetrabromoethane, of which the specific gravities are 2.90 when pure. Light minerals are those like quartz and feldspar, which float in such liquids. This method of separation is satisfactory if the diameters of the particles exceed 0.05 mm. When the particles have a smaller diameter they tend to float indefinitely, as the surfaces are so large with respect to mass. Of the stable minerals the larger number belongs to the heavy group. But the stable minerals of the light division are those most abundant and some of them are so universally present as to have little significance in interpretation.

Interpretation may be based on a single mineral, e.g., the use in the British Isles of purple zircons. This mineral also illustrates the important fact that the same mineral from a single source may recur and thus lose its value for correlation. Better practice relies upon assemblages of minerals, just as in modern stratigraphy reliance is placed on assemblages of fossils. Thus the mineral assemblage of a given horizon is likely to have distinct internal and external physical characteristics and distinct identities from the assemblage of another horizon. The quartz of one assemblage may have inclusions of a certain character, may appear strained, may have distinct colors, and may have marks of transportation which the minerals of another assemblage do not exhibit.

In the preparation of material for study the procedure will differ somewhat with the material. Sands may readily be separated into fractions by means of sieves, silts and clays are not thus separable and subsidation or other methods must be used. These methods are discussed and described in detail by Milner and in the chapter of this book on Field and Laboratory Studies of Sediments, and to these the student is referred.

The Coarser-grained Clastic Sedimentary Products

BY C. K. WENTWORTH

In this section are treated all clastic sedimentary products which normally contain in considerable number fragments of the size of sand grains

[34] Edson, F. C., Criteria for the recognition of heavy minerals occurring in the Mid-Continent Field, Bull. 31, Oklahoma Geol. Surv., 1925. Hatch, F. H., and Rastall, R. H., Petrology of the sedimentary rocks, London, 1913, revised ed., 1923. Holmes, A., Petrographic methods and calculations, London, 1918. Milner, H. B., Introduction to sedimentary petrography, London, 1922; Supplement to sedimentary petrography, London, 1926; Sedimentary petrography, London, 1929.

or larger. Included in this group are consolidated rocks, unconsolidated aggregates, and the constituent pieces. The number of different terms which have been applied to materials properly belonging in this category is very large; an effort has been made to include detailed discussion of the most common.

It is profitable in approaching a subject in which the range of materials and dimensions is as great as that comprehended in this section to attempt some sort of classification. Convenient presentation in tabular form suggests at once a dual classification in which the primary and secondary criteria are arranged as headings to vertical and horizontal columns. The attempt to classify such a group of natural objects as that in hand leads at once to the realization that they do not fall in a simple linear series or in a two-dimensional tabular scheme. Rather they seem to be arranged in small linear groups or as isolated points distributed in space in an extremely irregular fashion which defies simple tabular or graphic representation. The several characters by which a given coarse sediment may be allocated in any classification are the product in part of the agent and in part of the conditions of genesis; some of them are highly characteristic of the agent; others are more or less incidental and of little classificatory value. The more important characters which have been used in classifying the clastic sediments are:

Size and shape of grain
Mineralogical composition
Agent of formation

Since most of our existing terms connote a certain property on the basis of one or another of the above criteria and transgress so flagrantly the divisions resultant from the use of any other criteria, general classifications of sedimentary products have usually been more or less unsatisfactory to all but the classifier. Specific attempts to define more accurately a limited number of terms which fall in a series may meet with more success. References are given below to a number of classifications of sediments.[35]

The classification which follows is neither wholly genetic nor wholly based on size of grain, but rather is a combination of the two bases. This was

[35] Hatch, F.H., and Rastall, R.H., Classification of facies of deposition of sediments, The sedimentary rocks, London, 1913; Trowbridge, A. C., A classification of common sediments and some criteria for identification of the various classes, Jour. Geol., vol. 22, 1914, pp. 420–436; Mansfield, G. R., The characteristics of various types of conglomerates, Ibid., vol. 14, 1907, pp. 550–555; Grabau, A. W., Textbook of geology, Pt. I, New York, 1920, pp. 64–83, 556–581; Field, R. M., A preliminary paper on the origin and classification of intraformational conglomerates and breccias, Ottawa Naturalist, vol. 30, 1916, pp. 29–36, 47–52, 58, 66; Milner, H. B., Sedimentary petrography, London, 1929, pp. 266–267.

adopted as giving less duplication and cross reference than either and permitting the discussion in one place of such grain-size groups as sandstone or conglomerate on the one hand, and of such genetic groups as till or talus on the other.

GENERAL CHARACTERISTICS OF CLASTIC FRAGMENTS

Clastic fragments are pieces of pre-existing rocks which result from the disruption of the latter, and nearly all weathering processes have contributed to their formation.[36] Immediately following their release, the fragments are subject to transportation and to abrasion, as well as to other surface processes which are common to all exposed rocks. In the course of these processes the characters of size, shape, and surface texture of the individual pieces, and the size, range, and mineral and chemical composition of the aggregate deposit change in a manner characteristic of the manifold processes involved.

The shapes of pieces resulting from disruption are controlled by the nature of the parent rock and the condition of weathering. Little or no quantitative study has been made of the original shapes of rock fragments, in spite of the importance of this factor in determining their subsequent shapes as pebbles. The surface textures both of original and of transported fragments are due to the same factors that control their shapes, and this character likewise has been little investigated.

In the complex processes to which rock fragments are subjected at the surface of the earth, they fare differently according to their mineral and chemical composition, and only those which are best adapted to the rigor of their environment are able to withstand the chemical and physical processes to which they are subjected. As a result, there is in most regions a predominance of siliceous fragments in far-transported or long-weathered coarser clastic materials.

CONGLOMERATE AND GRAVEL

Conglomerate is a cemented clastic rock made up of rounded fragments larger than sand grains. It is the consolidated equivalent of gravel. There is considerable difference of usage as to limits between sand and gravel as well as to those separating other terms of this sort. A study has been made of these terms with a view to securing greater uniformity of usage, and table 24[37] gives the limiting sizes recommended. They conform closely to

[36] Blackwelder, E., Fire as an agent in rock weathering, Jour. Geol., vol. 35, 1927, pp. 134–140.

[37] Wentworth, C. K., A scale of grade and class terms for clastic sediments, Jour. Geol., vol. 30, 1922, pp. 377–392.

the average usage of a number of geologists and at the same time fit the standard screen scale used by Udden[38] and others in mechanical analysis.

Following the table, the several grades here considered may be defined as rounded fragments, or aggregates of such fragments, having the sizes indicated. No doubt many geologists have recognized the need for a generic term embracing rounded fragments of all the sizes which occur in gravels, including pebbles, cobbles, and boulders. Frequent reference to these in descriptions, where it is not desired to indicate a particular size, is difficult and to meet this difficulty the term *roundstone* has been suggested by F. A. Fernald.[39] It appears to be well adapted for this purpose and has been used in the revision of this section.

TABLE 24

THE GRADE TERMS

LIMITING DIMENSIONS	THE PIECES	THE AGGREGATE	THE INDURATED ROCK
mm.			
	Boulder	Boulder gravel	Boulder conglomerate
256			
	Cobble	Cobble gravel	Cobble conglomerate
64			
	Pebble	Pebble gravel	Pebble conglomerate
4			
	Granule	Granule gravel	Granule conglomerate
2			
	Very coarse sand grain	Very coarse sand	Very coarse sandstone
1			
	Coarse sand grain	Coarse sand	Coarse sandstone
1/2			
	Medium sand grain	Medium sand	Medium sandstone
1/4			
	Fine sand grain	Fine sand	Fine sandstone
1/8			
	Very fine sand	Very fine sand	Very fine sandstone
1/16			
	Silt particle	Silt	Siltstone
1/256			
	Clay particle	Clay	Claystone

The shapes of the constituent pebbles, cobbles, and boulders of gravels and conglomerates vary widely, though having the one essential characteristic of roundness. Comparatively little study has been made of the rounding of gravels beyond the simple observation that it takes place.

Likewise little quantitative work has been done on the shapes of pebbles,[40]

[38] Udden, J. A., Mechanical composition of clastic sediments, Bull. Geol. Soc. Am., vol. 25, 1914, pp. 655–744.

[39] Fernald, F. A., Roundstone, a new geologic term, Science, vol. 70, 1929, p. 240.

[40] Shrubsole, O. A., On the probable source of some of the pebbles of the Triassic pebble beds of South Devon and of the Midland counties, Quart. Jour. Geol. Soc., vol. 59, 1903, pp. 311–333; Wentworth, C. K., A laboratory and field study of cobble abrasion, Jour. Geol., vol. 27, 1919, pp. 507–522; The shapes of pebbles, Bull. 730-C, U. S. Geol. Surv., 1922, pp. 19–114; The shapes of beach pebbles, Prof. Paper 131-C, U. S. Geol. Surv., pp. 75–83; Quantitative studies of the shapes of pebbles, Unpublished thesis, Univ. Iowa, 1921, pp. 4–9; Note on a cobble of peculiar shape, Jour. Geol., vol. 32, 1924, pp. 524–528; Chink-faceting, Ibid., vol. 33, 1925, pp. 260–267; Tolman, C. F., Erosion and deposition in the southern Arizona bolson region, Ibid., vol. 17, 1909, pp. 136–163; Gregory, H. E., Notes on the shapes of pebbles, Am. Jour. Sci., vol. 39, 1915, pp. 300–304.

and the lack of exact data in this field has led to the feeling on the part of some geologists that shapes of pebbles are of little value in interpreting the history of deposits in which they occur. The results of considerable laboratory and field study of the shapes and rounding of pebbles have led to the following conclusions, of which some are supported by a considerable amount of quantitative study; others are views based upon reading and observations and doubtless subject to considerable revision and reformulation in the light of more detailed investigation.

1. The original shape of the rock fragment is a very important factor in the development of the shape of the pebble. During the early stages it is

FIG. 14. ROCK FRAGMENTS PRODUCED BY THE BREAKING OF SHALE
The shapes of the fragments are controlled by the detailed structure of the formation. Pennsylvanian shale, southeast of Norton, Virginia. Photograph by C. K. Wentworth, U. S. Geol. Surv.

dominant, and it is persistent throughout a long part of the history of the pebble (fig. 14). This is particularly true because there are probably very few realms of pebble shaping by streams or on beaches where violent fragmentation is the rule; for the most part the shaping is accomplished by slow abrasion or by a battering of the exposed edges and corners which is only moderately violent.[41,42] Where true fragmentation takes place, as a general

[41] For definitions of terms abrasion, impact, grinding, and wear see: Marshall, P., The wearing of beach gravels, Trans. New Zealand Inst., vol. 58, 1927, p. 518, and Wentworth, C. K., Pebble wear on the Jarvis Island beach, Washington Univ. Studies, Sci. and Tech. Ser., vol. 5, 1931, pp. 23–26.

[42] Barrell, J., Marine and terrestrial conglomerates, Bull. Geol. Soc. Am., vol. 36, 1925, pp. 291–341.

rule rounding in the sense of an approach to sphericity can hardly be prominent; in most situations fragmentation is sufficiently rare so that the partially rounded cobble from which a large spall has been removed is commonly identifiable as such for a large part of its subsequent history.

2. The structure and texture of the material of a pebble is a dominant factor in the development of pebble shape. Rounded forms can result from the abrasion of any kind of rock, but only nearly homogeneous, non-schistose rock will yield pebbles of spheroidal form.

3. Flat surfaces, whether original fracture planes or abraded facets, are relatively more persistent than sharp angles of any origin.

4. The durability of different kinds of rock, when subjected to abrasion in streams, shows wide variation, the ratio between a hard granite and a soft chalky limestone being of the order of 100 to 1. Cozzens found that under different conditions of wear, gypsum ranged from 1/160 to 1/500, approximately, of the durability of quartz and that several minerals were considerably more durable than quartz. Similar ratios are implied in the results of various graving or scratch tests.[43]

5. The shapes developed by artificial abrasion of angular fragments in a tumbling mill and those developed by abrasion in natural streams of relatively high gradient and moderate load in a humid region are closely similar. In the relative rates of wear on corners and sides, and in the details of the approach toward spherical forms, there seems to be little difference between the two methods. In streams of this sort, universally oriented tumbling and bumping seem to be dominant, and sliding, lateral rolling, or any other special sort of motion seems to be quite subordinate.[44]

6. River gravels of homogeneous rocks have forms which are in direct transition from angular, irregular forms to spheroidal ones. That river gravels may in certain situations be shaped by specially oriented abrasion while they lie in one position, or that they may also in some places be given flat, smoothed forms by sliding along the stream beds is probable; but these conditions appear to be very special, and such results are not typical of river action in general. Spheroidal, discoidal, and other shapes are developed. In the piedmont regions sorting, stratification, continuity of beds, and rounding are all extremely limited. Great thickness and distribution are possible (figs. 15 and 16).

7. Beach gravels from some beaches are notably flat and ellipsoidal or discoid in form even when composed of massive igneous rocks, but it does

[43] Cozzens, A. B., Rates of wear of common minerals, Washington Univ. Studies, Sci. and Tech. Ser. vol. 5, 1931, pp. 74–75.

[44] Grabau, A. W., Principles of stratigraphy, 1913, pp. 246–247. Wentworth, C. K., Bull. 730-C. U. S. Geol. Surv., 1922, p. 113.

not seem that these flat smoothed forms are typical of beach action in general. While they occur in abundance on certain portions of some beaches, this may be the consequence of the segregation of such gravels by sorting or the resultant of the original shapes. Along many rocky coasts where there is little fine material in the beaches, the gravel is made up of notably spheroidal roundstone with a few of the roller-shaped and other types. Here the beach action appears to be a powerful milling with a dominant tendency toward sphericity if the rock material be massive in structure. A recent study of the movement of beach pebbles on the shore of Lake Michigan has led to the conclusion that angular fragments are first rounded and

FIG. 15. RIVER GRAVEL IN FLOOD PLAIN OF POWELL RIVER NEAR TOWN OF BIG STONE GAP, VIRGINIA

Stream flowed from right to left. Photograph by C. K. Wentworth, U. S. Geol. Surv.

that these in turn become further flattened with transport and wear. The importance of both selective sorting and specialized wear is recognized but it seems to the present writer that it is scarcely possible on the basis of the data presented to estimate the true value of either of these alone, and it is doubted whether any generally applicable pronouncement can be made.[45] Beach gravels may have extensive distribution, but the thickness is limited (figs. 17 and 18).

8. Glacially shaped fragments, as a rule, have flatter facets and less

[45] Landon, R. E., An analysis of beach pebble abrasion and transportation, Jour. Geol., vol. 38, 1930, pp. 437–446.

sharp angles than sand-blasted fragments. They may or may not have glacial striæ. Pebbles so marked are likely to be rare, and if common in a deposit, comparatively little extra-glacial transportation is indicated. Great extent and thickness are possible.

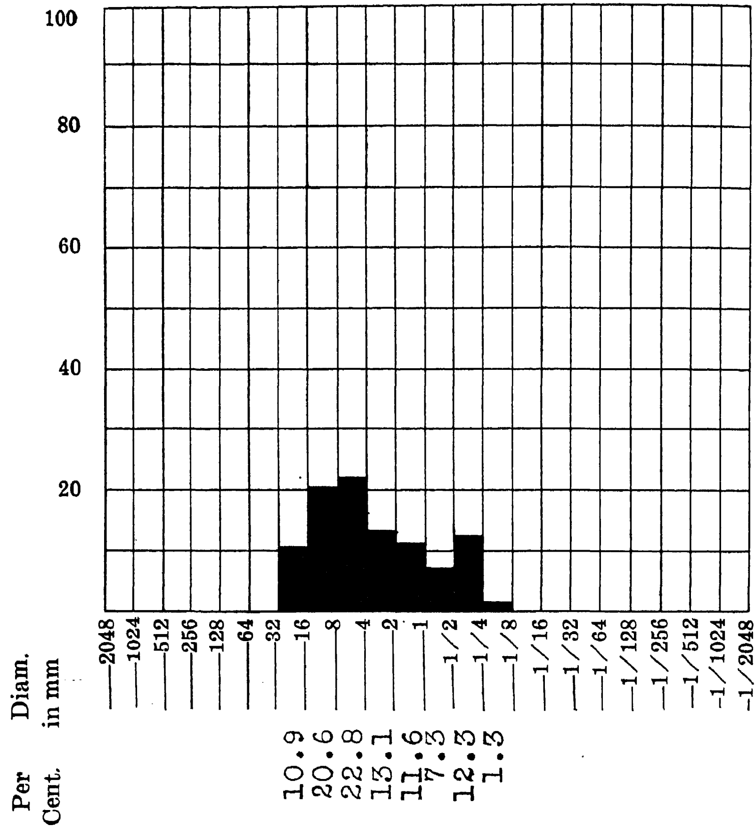

FIG. 16. MECHANICAL ANALYSIS OF RIVER GRAVEL

Analysis by J. A. Udden (No. 79). Sample from Klondike River near Dunraven, Alaska.

Referring especially to modern valley glaciers, emphasis needs to be placed on the fact that most of the débris of medial moraines is nearly unmodified, angular rock débris, that considerable rounding of cobbles is wrought by superglacial and subglacial streams, and that only a small part of the material of the terminal moraine is commonly composed of ideal, facetted and striated fragments.

9. Sand-blasted fragments have facets which are commonly less flat than those of abraded glacial stones and likely to be warped in one direction. The surfaces are pitted, etched, and polished, and if composed of hard material like chert, the polish becomes almost mirror-like. Deposits are extremely limited in thickness and distribution. Rates or effectiveness of sandblasting by the wind may in some instances be estimated by the effects present or absent on materials of known durability. Thus, Schoewe and Bryan conclude that bright cleavage fragments of selenite indicate complete absence of significant wind action.[46] Other such criteria are suggested by this conclusion. Various geologists have noted evidences of sand-blast

FIG. 17. MARINE BEACH GRAVEL

Gravel composed mainly of granite boulders, Massachusetts coast, south of Rockport. Photograph by C. K. Wentworth, U. S. Geol. Surv.

effects which were probably wrought under exceptionally windy conditions combined with lack of vegetation and exposure of much rock débris, such as followed closely the deglaciation of various parts of northern United States. The writer has noted sandblasted ledges and large boulders in Wisconsin, Montana and Wyoming, in all these places closely associated with glacial features and clearly not now being abraded. Blackwelder has described similar phenomena in the Sierra Nevada of California.[47]

[46] Schoewe, W. H., and Bryan, K., Selenite fragments or crystals as criteria of wind action, Science, vol. 72, 1930, pp. 169–170.

[47] Blackwelder, Eliot, Sandblast action in regard to the glaciers of the Sierra Nevada, Jour. Geol., vol. 37, 1929, pp. 256–260.

10. Residual gravels are of extremely irregular shapes and dimensions and are as a rule deeply pitted by corrosion. Those of chert may attain considerable thickness.

The results of an extended series of experiments on the laboratory shaping of pebbles have been presented by Marshall. He distinguishes the three processes, abrasion, impact and grinding; the latter the crushing of small

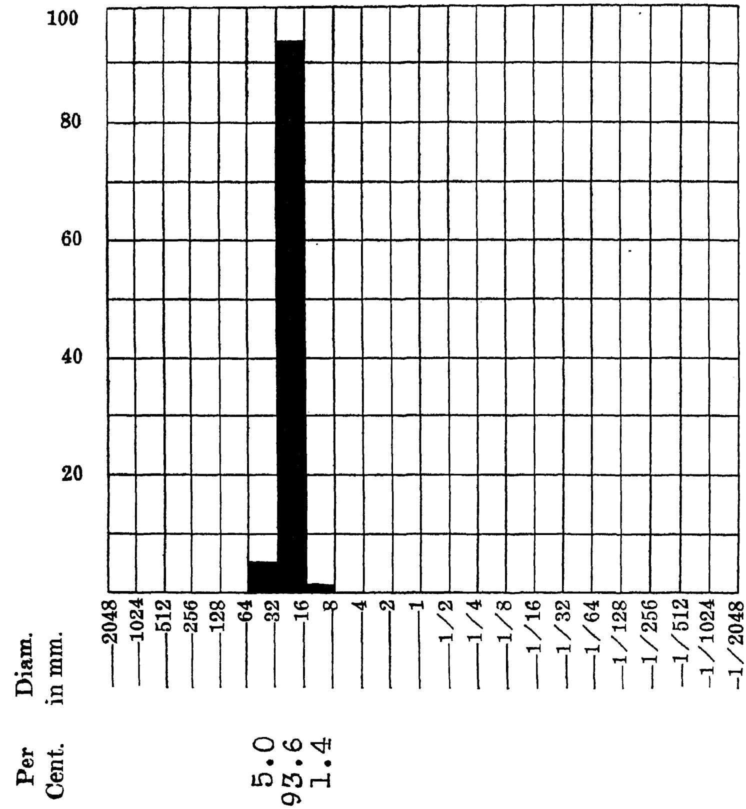

Fig. 18. Mechanical Composition of Beach Gravel

Analysis by C. K. Wentworth (No. 10731). Sample from Long Beach, north of Gloucester, Massachusetts.

fragments by larger. Under the conditions used, grinding was the most rapid and abrasion the least rapid of the processes, though it is recognized that these results might be somewhat modified with different dimensions of the tumbling chamber and other variations of the conditions. A number of other conclusions are presented, for which the reader must be referred to

the original paper.[48] Additional studies have recently been made by the present writer dealing with pebble wear in general and with rates of water on a tropical beach recorded by the shaping of coal pebbles in a known length of time. An attempt has been made in these studies to conventionalize still further the standards of wear and the terminology for process of wear, commencing with the distinctions presented above.[49]

Various studies, both of natural river gravel, and of the wearing of rock fragments in a mill, have indicated that the wear tends to be at least approximately proportional to the weight of the pebble and to the distance traveled. This relation, which has been called Sternberg's law, is an exponential relation which has been elaborated by Barrell.[50] In the terminology adopted by the writer, in which the reduction index is defined as the loss in weight in parts per million per meter (= parts per thousand per kilometer), Sternberg's law is identical with the finding that the reduction index is a constant essentially independent of size.[51] When one realizes the unexplored complexity of the process of pebble-wear it is evident that this law can only be a very useful first approximation rather than a rigorous law with a rational basis.

The surfaces of rounded fragments are considerably smoother than the unabraded fracture surfaces of the rocks of which they are composed. When abrasion has been recent and active enough to remove all products of concurrent weathering, the surfaces of the pebbles composed of hard rocks are clean and show beautiful cross sections of their structure. Chert pebbles are notable for the high polish sometimes developed on their surfaces. Pebbles found within beds of clay in some instances also have smooth and polished surfaces.

The bedding of gravels and conglomerates is extremely variable, and they rarely, if ever, possess the continuity of bedding common to finer clastie sediments or limestones. In very coarse conglomerates bedding may bc almost wholly absent, the boulders resting on one another almost as in talus and the crevices chinked in with smaller pebbles and sand. Only in viewing the structure of such a conglomerate as a whole, will the stratified

[48] Marshall, P., The wearing of beach gravels, Trans. New Zealand Inst., vol. 58, 1927, pp. 507–532; Also Beach gravels and sands, Ibid., vol. 60, 1929, pp. 324–365.

[49] Wentworth, C. K., Pebble wear on the Jarvis Island beach, Washington Univ. Stud., Sci. and Tech. Ser., vol. 5, 1931, pp. 23–26.

[50] Sternberg, H., Untersuchungen über Längen- und Querprofil geschiebeführende Flüsse, Zeits. f. Bauwesen, vol. 25, 1875, pp. 483–506. Barrell, J., Marine and terrestrial conglomerates, Bull. Geol. Soc. Am., vol. 36, pp. 325–330.

[51] Wentworth, C. K., Pebble wear on the Jarvis Island beach, Washington Univ. Stud., Sci. and Tech. Ser., vol. 5, 1931, pp. 11–37.

character be apparent. The base of a conglomerate is usually more sharply limited than the top, since the conglomerate commonly grades upward to finer sediments. Zones of cross-bedding in conglomerates locally may show a row of pebbles at the base of the cross-bedding, to which they were rolled as the foreset beds advanced. Particles which are considerably longer and broader than thick commonly lie with their long axes parallel to the bedding if they are not abundant. If abundant, they are sometimes imbricated[52] in beach gravels, the long axes of the particles dipping seaward or down the slope of the deposit, and in stream gravels dipping upstream. In gravels which are poorly assorted, the particles lie at random with comparatively little orderly arrangement. Many such accumulations contain only a small proportion of fragments of pebble size or larger, but when they are part of terrace formations or similar deposits they are commonly called gravels. River gravels show a cut and fill or flow and plunge structure resulting from the rapid changes in directions and velocities of current and the alternation of erosion and deposition. Such deposits may show little order in the distribution of coarse materials, these being often quite as common at the top as at the base.

Considered without reference to total quantity or distribution, the lithologic and mineralogical constituents of gravels and conglomerates are as diverse as the rocks and minerals from which they come, although most are composed of only one or two varieties of rock.[53] All types of igneous and metamorphic rocks and minerals, clastic rocks, and limestone furnish pebbles which are found in gravels. Coal, peat, wood, clay, native metals, heavy ores, shells, bone, ivory, as well as the abraded relics of every sort of industrial material, are found in modern gravels.

The growths of some algæ and various corals are frequently spheroidal in shape and of dimensions very similar to those of gravels, for which they may very readily be mistaken. Every limestone conglomerate should therefore have its particles broken. In some localities concretions from adjacent deposits accumulate to form a greater or less proportion of the gravels. These need to be discriminated from the associated particles, for the bearing they have on the origin. In general, the lithologic composition of all

[52] Barrell, J., Dominantly fluviatile origin under seasonal rainfall of the Old Red Sandstone, Abst., Bull. Geol. Soc. Am., vol. 27, 1916, pp. 39–40; Jamieson, T. F., On the drift and rolled gravel of the north of Scotland, Quart. Jour. Geol. Soc., vol. 16, 1860, p. 349; Johnston, W. A., Imbricated structure in river gravels, vol. 4, 1922, pp. 387–390; Pettijohn, F. J., Imbricate arrangement of pebbles in a pre-Cambrian conglomerate, Jour. Geol., vol. 38, 1930, pp. 568–573.

[53] Roberts, J. K., The geology of the Virginia Triassic, Bull. 29, Virginia Geol. Surv., 1928, pp. 9–24.

gravels and conglomerates should be of immense assistance in interpreting their origin and history.[54]

The lithologic composition of gravels may usually be regarded as in a transition from the heterogeneity of the original collection of rock fragments to the homogeneous and commonly quartzose character of far-traveled gravels. Though the increase of proportion of the siliceous constituents is practically, if not quite, universal, it is probable that there are great differences in the rate of elimination of various constituents in different climates. Gravels composed mainly of quartz, which have been derived from a source yielding fragments of other minerals, are clearly the result of prolonged weathering or transportation or both, whereas gravels containing abundant pebbles of basic igneous rock, granite, limestone, or feldspar, or other easily destructible minerals, are the result of less prolonged processes or of conditions peculiarly favorable for the preservation of these constituents. Beyond these broader generalities, little is known specifically of the behavior of various rocks and minerals as constituents of gravels, and the subject offers some very promising problems for investigation.

A gravel may contain particles weathered from a pre-existing conglomerate, and some particles of resistant rock have doubtless formed parts of many successive formations from early geologic time, and almost all gravels probably contain at least a few such second-generation pebbles. In some cases evidence may be found to prove such a history and yield many valuable paleogeographic data, but in the great majority of cases the evidence has long since been lost.

The surface characteristics of the roundstones of gravels depend to a certain extent on the hardness and structure of the material. Those composed of hard, homogeneous rocks such as quartzite are smooth and clean, whereas those composed of sandstone or easily weathered igneous rocks commonly show weathered, pitted surfaces. Rapid abrasion with slow decomposition produces smooth clean surfaces. Boulders of fine-grained rock, such as chert, not uncommonly show numerous crescentic surfaces or impact scars of the shape which one might make in soft material with a thumb nail. These are produced by the impacts between boulders and are roughly in accord with the size of the boulder. They vary from 2 or 3 inches in diameter on large boulders to a millimeter or less on smaller pebbles. After deposition, ground-water action may eliminate the smoothness and also the impact scars.

The cementation of gravels to form conglomerates varies within wide limits. Some conglomerates are so firmly cemented that they break across

[54] Holmes, A., Petrographic methods and calculations, London, 1921, pp. 160–230.

the roundstones while in others the cementation has been so slight that they may be dug with steam shovels for road material, although in some cases this is the result of weathering. Many comparatively young geologic formations, especially those of terrestrial origin, are only imperfectly and irregularly cemented.[55] The new term *conglomerite* has recently been suggested to designate a conglomerate which is sufficiently quartzitic to cause the rock to break through the contained pebbles rather than around them.[56]

Because of the common occurrence of pebbles and boulders in the lower parts of formations which immediately overlie an unconformity, the term basal conglomerate has come to be widely used. The term may be appropriate in some cases, but it seems clear that in the case of marine formations the accumulation is marginal rather than basal, and hence the term marginal conglomerate would appear to be more properly applicable in many instances. One of the most comprehensive descriptions of the characteristics of any series of conglomerates is that by Hadding on the Paleozoic and Mesozoic conglomerates of Sweden, which presents a large amount of descriptive matter as well as a very useful analysis of the various features of conglomerates and a detailed genetic classification.[57]

Boulders

Boulders range in size from the lower limit of about 25 cm. up to several meters in diameter. Large boulders are commonly poorly rounded and grade into blocks which have been so little rounded as not to merit the name. The largest water-carried boulders occur in the high-gradient streams of mountain regions or on storm-beaten coasts, where the competency of moving water is high. Trowbridge has shown that in some situations very large boulders are slowly moved down the slopes of far deposits by a process of undermining.[58] Boulders of many meters in diameter are transported by glacial ice, and not uncommonly boulders of exceptional size are transported by floating ice or held in the roots of floating trees. They are also floated far out to sea by icebergs[59] or by timber rafts and by seaweeds which have clung to them.

[55] Trowbridge, A. C., Reynosa formation in lower Rio Grande region, Texas, Bull. Geol. Soc. Am., vol. 37, 1926, pp. 455–462.

[56] Willard, B., Conglomerite, a new rock term, Science, vol. 71, 1930, p. 438.

[57] Hadding, A., The Paleozoic and Mesozoic conglomerates of Sweden, Lunds Universitets Arsskrift, N. F., Avd. 2, Bd. 23, Nr. 5, Pt. II, 1927, pp. 43–171.

[58] Trowbridge, A. C., Terrestrial deposits of Owen's Valley, California, Jour. Geol., vol. 19, 1911, pp. 706–747.

[59] Murray and Hjort (Depths of the ocean, London, 1912, pp. 207–208) state that boulders dropped from icebergs stick in muds with long axes vertical, though this behavior is contrary to the physical principles involved and to the behavior of flat objects falling in air.

In relatively few of the situations where boulders are found are they so completely rounded as to obscure the original shapes of the blocks from which they were made. The most effective rounding is accomplished in pocket beaches and proceeds in two ways. The corners are first broken off. When the general roundness of the edge has reached a stage adjusted to the size of the boulder, the subsequent rounding is mainly produced by slow grinding. In streams where boulders lie exposed to weathering through much of the year, they are not uncommonly riven along incipient joint planes and show henceforth two generations of rounded edges. Such incidents are readily interpretable by inspection long after they have occurred. Boulders of hard compact rocks which lie in one position in channels for long periods sometimes are gouged and grooved, or have curious funnels cut in them by the abrasion of lesser detritus which passes over them. Potholes passing entirely through such boulders are known.

Boulders of homogeneous rocks such as granite become nearer and nearer spherical in shape as they are rounded, but most rocks yield boulders which because of unequal durability in different directions are ellipsoidal or ovoid in form. These flat, rounded boulders are common on some beaches,[60] but it does not seem that such shapes are strong proof of beach action.[61]

Exposed rocks may become rounded by spheroidal weathering, and such products also have been called boulders. They are not always easily distinguishable from true boulders.

Rock fragments which stand for long periods of time in stream channels, on desert surfaces, or in any situation where certain characteristic chemical or physical forces act, acquire distinctive surface features and in some instances the interior is altered as well. Case-hardening is the result of a more complete cementation along joint surfaces or on the smoothed and rounded surfaces of roundstones. Not uncommonly this is well shown on the flatter surfaces of a boulder, where the corners and edges are rougher by virtue of a more vigorous and recent battering.

Desert varnish is a name given to dark brown and black coatings of iron and manganese oxide which occur on rocks in desert regions. It has generally been thought to be the result of deposition of mineral material from evaporated capillary water. A recent study indicates that in some instances, at least, the growth of lichens may be an important contributing factor.[62] Chert pebbles not uncommonly undergo a bleaching under certain surface conditions.

[60] Barrell, J., Dominantly fluviatile origin under seasonal rainfall of the Old Red Sandstone, Abst. Bull. Geol. Soc. Am., vol. 27, 1916, pp. 39–40.

[61] Wentworth, C. K., The shapes of pebbles, Bull. 730-C, U. S. Geol. Surv., 1922, pp. 91–114.

[62] Laudermilk, J. D., On the origin of desert varnish, Am. Jour. Sci., vol. 21, 1931, pp. 51–66.

Boulders are composed in the main of hard, durable rocks. Boulders of softer rocks are mostly limited to the immediate area of their derivation, but ice or tree rafting may give them long transportation.[63] Two types of clayballs may be distinguished; those which are rounded by true abrasion and those which are rounded by moulding or accretion. Roundstones of clay may become studded with pebbles and thus simulate roundstones of conglomerate. Under favorable conditions such roundstones may be incorporated into sedimentary deposits and are well known in some formations. Several instances of clayball formation have been described by Haas.[64] Boulders may also be composed of peat (fig. 19).

FIG. 19. BOULDERS OF PEAT ON ALLUVIAL FAN. STATE ROAD ON LOWER BUFFALO RIVER, WISCONSIN
Photograph by F. T. Thwaites, Wisconsin Geol. Surv.

Cobbles

Cobbles or cobblestones are defined as rounded stones intermediate in size between boulders and pebbles, from which they are distinguished on the basis of size. Their various characteristics and modes of occurrence are similar to those of larger and smaller roundstones.

Pebbles

Pebbles are small, rounded or abraded fragments of rock, ranging in size from 4 to 64 mm. in diameter. The sizes depend in part on the sizes of rock

[63] Von Engeln, O. D., Transportation of debris by icebergs, Jour. Geol., vol. 26, 1918, pp. 74–81.

[64] Haas, W. H., Formation of clayballs, Jour. Geol., vol. 35, 1927, pp. 150–157.

fragments available and in part on the nature and extent of transportation. Much valuable information on pebbles is to be found in papers by Jones, Hewitt, and other British students of sedimentary petrography.[65]

In general, pebbles are probably more symmetrical and better rounded than cobbles or boulders but pebbles of all degrees of roundness occur in both modern and ancient deposits. Since the roundness of a given pebble is a function of its hardness and of the duration and rigor of the abrasion to which it has been subjected, it would appear that this characteristic, when quantitatively studied in relation to these factors, will be of great value in interpreting geologic history. It has been found experimentally that there is variation of at least two or three hundred fold in the durability of different common rocks in stream transportation, and consequently great variations in the significance of a given degree of rounding in hard and soft rocks. In terms of the roundness ratio used by Wentworth, it may be stated that pebbles which are 50 per cent rounded, that is, approaching halfway from angularity to sphericity, are extremely rare, though such may be found. It is not known that a gravel or conglomerate exists in which the average pebble even approaches this degree of rounding. These facts serve to emphasize the danger of over-estimating the roundness and symmetry of pebbles in ordinary, casual observation. This is particularly true if the pebbles be well exposed, clean, smooth, and generally pretty. In order to have permanent comparative value even to the individual who made them, observations on the shapes and rounding of pebbles must include all material within certain arbitrary space boundaries and the mode of collection and study must be stated. Methods of measuring the roundness of pebbles have been devised by Cox and by Tester[66] as well as by the present writer.

In consonance with statements made above in regard to roundness, the fact should be emphasized that only a small proportion of all pebbles are so well rounded and smoothed as to remove all traces of the original shapes. By far the greater part show clearly the general form, and not uncommonly many of the details of the shape of the original angular fragments.

Granules

Granules are rock particles between 2 and 4 mm. in diameter and are intermediate in dimension between pebbles and coarse sand grains. Since

[65] Jones, T. A., Petrographical studies of local erratics, Proc. Liverpool Geol. Soc., vol. 11, 1912, pp. 183–200; Ibid., vol. 12, 1920, pp. 281–308, 347–354; Hewitt, W., Notes on pebbles and their geological associations, Ibid., vol. 12, 1920, pp. 383–407; Holmes, A., Petrographic methods and calculations, London, 1921, pp. 160–230.

[66] Cox, E. P., A method of assigning numerical and percentage values to the degree of roundness of sand grains, Jour. Paleont., vol. 1, 1927, pp. 179–183; Tester, A. C., The measurement of the shape of rock particles, Jour. Sed. Pet., vol. 1, 1931, pp. 3–11; Tester, A. C., and Bay, H. X., The shapometer: a device for measuring the shapes of pebbles, Science, vol. 73, 1931, pp. 565–566.

they partake of the characters of pebbles on the one hand and sand grains on the other, they will not be separately described.

Shingle

Shingle is a term applied by English geologists to the coarser gravel of beaches. Similar material is usually described by American geologists as gravel.

Faceted Roundstones

Among the most common variations of the forms of pebbles, cobbles, or boulders, is the presence on the surface of the fragment of one or more flat or curved facets. Some of these, such as those of glacial origin and those formed by sand-blasting, are quite characteristic and well known; others are not so well known, and new types, resulting from some peculiar but quantitatively subordinate processes, are being described at frequent intervals. Facets may be due to glacial abrasion on the subglacial pavement, to stream-line carving by the wind as in the case of dreikanter and related forms, to the residual preservation of a joint-formed flat below the freshly lapped surface formed by milling in a pothole,[67] to the abrasion of roundstones in the chinks of a stable and coarse beach gravel,[68] to the superior preservation of better-cemented joint surfaces in the course of normal stream transport,[69] and probably many other processes, some of which are tectonic rather than sedimentary.[70] The importance of ice jams in arctic rivers in producing striated and somewhat faceted roundstones will be developed in a forthcoming paper by the present writer.

Intraformational conglomerates[71]

As defined by Walcott, these are conglomerates developed by the breaking up of a partially consolidated bed and the incorporation of the fragments in new strata nearly contemporaneous with the original beds. Such are

[67] Wentworth, C. K., Note on a cobble of peculiar shape, Jour. Geol., vol. 32, 1924, pp. 524–528.

[68] Wentworth, C. K., Chink-faceting, a new process of pebble-shaping, Jour. Geol., vol. 33, 1925, pp. 260–267.

[69] Steidtmann, E., Faceted sandstone pebbles of the North River near Lexington, Virginia, Jour. Geol., vol. 34, 1926, pp. 836–839.

[70] Voitesti, I. P., Galets à facettes, Compt. Rend., Acad. Sci., Paris, vol. 180, 1925, pp. 1113 et seq.

[71] Walcott, C. D., Paleozoic intraformational conglomerates, Bull. Geol. Soc. Am., vol. 5, 1894, pp. 191–198; Field, R. M., A preliminary paper on the origin and classification of intraformational conglomerates and breccias, Ottawa Naturalist, vol. 30, 1916, pp. 29–36, 47–52, 58–66; Fillman, L., On the supposed limestone conglomerate of the northern Black-Hills of South Dakota, Unpublished thesis, University of Iowa, 1921.

known to be developed under marine conditions, where partially consolidated materials are torn up by strong waves and redeposited. Laminæ and bedding planes arch downward between the fragments and these lie in all sorts of positions. Intraformational conglomerates are also developed over mud-cracked surfaces after the blocks are jumbled together by strong wind or rapid water action. Thin layers of conglomerates or breccias result. This type is characteristic of playas. Conglomerates of intraformational composition appear also to have been formed by corrosion and the subsequent incorporation in sediments of relatively insoluble residues which remained.[72] These conglomerates should not be confused with other conglomerates within a formation of which the particles are derived from earlier rocks.

Edgewise Conglomerates[73]

Edgewise conglomerates have the pebbles transverse to the bedding. They may be developed by the rapid deposition of the material composing the conglomerate, by slumping after deposition, or in the normal production of an intraformational conglomerate. They are common in the Cambrian of western Wisconsin and in the Cambrian and Ordovician of eastern Pennsylvania,[74] as well as in the Deadwood formation of the Big Horn Mountains and Black Hills regions.

Pseudoconglomerates

Structures which resemble but are not conglomerates develop through the growth of concretionary structures, and the mammillary surfaces which occur on the summits of some algal growths, as for instance the cryptozoan algæ of the Oneota dolomite of the upper Mississippi Valley, also may resemble conglomerates.

Criteria of Origin of Conglomerates

The two principal types of gravels and conglomerates are those of fluviatile and marine origin. Though the very great abundance of fluviatile sediments has only gradually been recognized by geologists, it is probable that in the case of the coarser clastic rocks those of fluviatile origin are of far greater quantitative importance than those of marine origin. Barrell made a very careful analysis of all the conditions of the two types of erosion

[72] Pettijohn, E. J., Intraformational phosphate pebbles of the Twin City Ordovician, Jour. Geol., vol. 34, 1926, pp. 361–373.

[73] Fillman, L., op. cit.

[74] Stose, G. W., Folio 170, U. S. Geol. Surv., 1909; Brown, T. C., Jour. Geol., vol. 21, 1913, p. 232; Field, R. M., op. cit., 1916.

and concluded that the fluviatile gravels produced annually were some tens of times as large in amount as those produced by marine agencies.[75]

It is not proposed to describe at length here the criteria which have been used in interpreting the origin of conglomerates. Very much work remains to be done before satisfactory criteria of origin can be stated, and it is probably easier and far more profitable to consider the problem of origin of a given conglomerate on its merits than to attempt to formulate at present any general tabular scheme for the recognition of different types.[76] In general, it may be stated that thick conglomerates suggest a continental origin. In many instances a conclusion as to the origin of gravel formations which are related to the modern surface can be reached only by considering physiographic as well as petrographic and structural criteria.[77] Additional consideration is given to the matter in the chapter on environments.

SANDSTONE AND SAND

Sandstone is a rock made up of small rounded or angular grains of mineral or rock fragments which have been derived from some pre-existing rock. It will be noted that whereas the particles or phenoclasts of conglomerate are by definition rounded, those of sandstone may be either rounded or angular. Sandstones are but cemented and consolidated sands, and the following description of the latter applies to the former also except for the features related to the cementation and consolidation.

Sand grains have been variously defined as to size, but will here be considered as ranging from 1/16 to 2 mm. in diameter. Deposits of sand occur in which large proportions of the grains fall within limits much closer together than those named above. Other deposits range in composition from pebbles and granules above to fine silt and clay below, with proportionately less sand. In still other deposits sand is a subordinate constituent as a

[75] Barrell, J., Marine and terrestrial conglomerates, Bull. Geol. Soc. Am., vol. 36, 1925, p. 291.

[76] Gilbert, C. J., Deposits of high level sands and gravels at Little Heath, Quart. Jour. Geol. Soc., vol. 75, 1919, pp. 32–43; Shrubsole, O. A., On the probable source of some of the pebbles of the Triassic pebble beds of South Devon and of the Midland Counties, Quart. Jour. Geol. Soc., vol. 59, 1903, pp. 311–333; Barrell, J., Dominantly fluviatile origin under seasonal rainfall of the Old Red Sandstone, Abst., Bull. Geol. Soc. Am., vol. 27, 1916, pp.39–40; (Origin of the Gila conglomerate), Jour. Geol., vol. 16, 1908, p. 174; Gregory, H. E., The formation and distribution of fluviatile and marine gravels, Am. Jour. Sci., vol. 39, 1915, pp. 487–508; Lawson, A. C., The petrographic designation of alluvial fan formations, Univ. California Publ., Dept. Geol., vol. 7, no. 15, 1913; Moncton, H. W., On some gravels of the Bagshot district, Quart. Jour. Geol. Soc., vol. 54, 1898, p. 184; Hobbs, W. H., Guadix formation of Granada, Spain, Bull. Geol. Soc. Am., vol. 17, 1906, p. 292.

[77] Wentworth, C. K., Sand and gravel resources of the coastal plain of Virginia, Bull. 32, Virginia Geol. Surv., 1930, pp. 100–105.

matrix in coarse conglomerate or in the form of scattered coarse grains in a silt or clay. Mechanical analyses of several different kinds of sand are given in figures 20 to 22, not so much to show types as to show the range in the perfection of sorting of sands.

Efforts have been made by geologists to use the mechanical composition

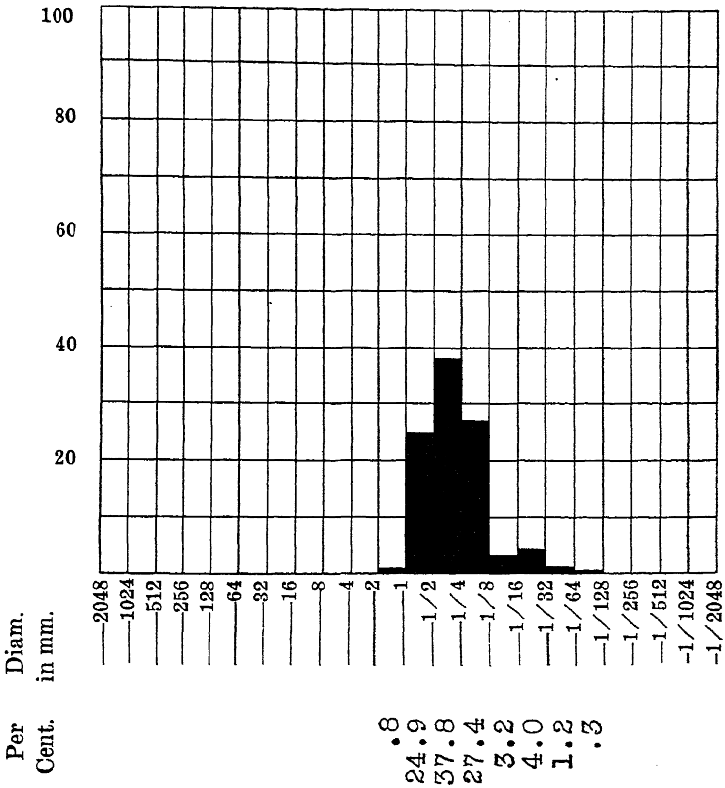

FIG. 20. MECHANICAL COMPOSITION OF RIVER SAND
Analysis by J. A. Udden (No. 65). Sample from a creek at Linwood, Iowa

of sediments in diagnosing their origin.[78] From a study of a large number of mechanical analyses, Udden has formulated certain general characteristics of sediments of different sorts.[79] He finds that wind-laid deposits are in

[78] Shaw, E. W., Significance of sorting in sedimentary rocks, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 925–932; Baker, H. A., On the investigation of the mechanical composition of loose arenaceous sediments by the method of elutriation, Geol. Mag., vol. 77, 1920, pp. 321–332, 363–370, 411–420, 463–467; Lugn, A. L., Sedimentation in the Mississippi River, Augustana Library Publ., no. 11, 1927, pp. 1–104.

[79] Udden, J. A., Mechanical composition of clastic sediments, Bull. Geol. Soc. Am., vol. 25, 1914, pp. 655–744.

general more perfectly assorted than water-laid deposits, though he recognizes some exceptions. Between these two types there is also a difference in the distance between the primary and secondary maximum grades, these maxima being farther apart in the water-laid than in the wind-laid deposits.

Inasmuch as the sorting of sedimentary particles results in a frequency distribution of particle sizes showing one or more strong central tendencies,

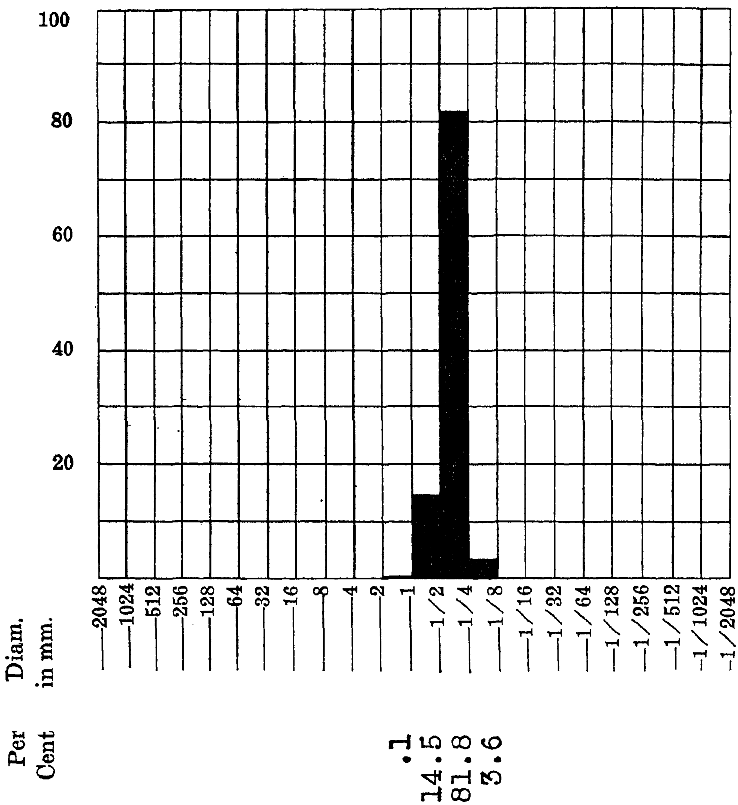

Fig. 21. Mechanical Composition of Beach Sand

Analysis by C. K. Wentworth (No. 10741A). Sample from beach south of Asbury Park, New Jersey.

it is the belief of the present writer that future refinements of interpretation must follow well established statistical procedures. Accordingly a method of computing the diagnostic constants of mechanical composition has been adapted and described.[80]

[80] Wentworth, C. K., Method for computing mechanical composition types of sediments, Bull. Geol. Soc. Am., vol. 40, 1929, pp. 771–790.

The shapes of sand grains have been used by many students as criteria for the determination of origin of sands,[81] but no record of accurate measurements of roundness of sand grains has been published.[82] In published works the most precise discriminations are those in which grains have been identified as rounded, subrounded, subangular, and angular, and the results averaged by assigning numbers to those terms. As a result of preliminary

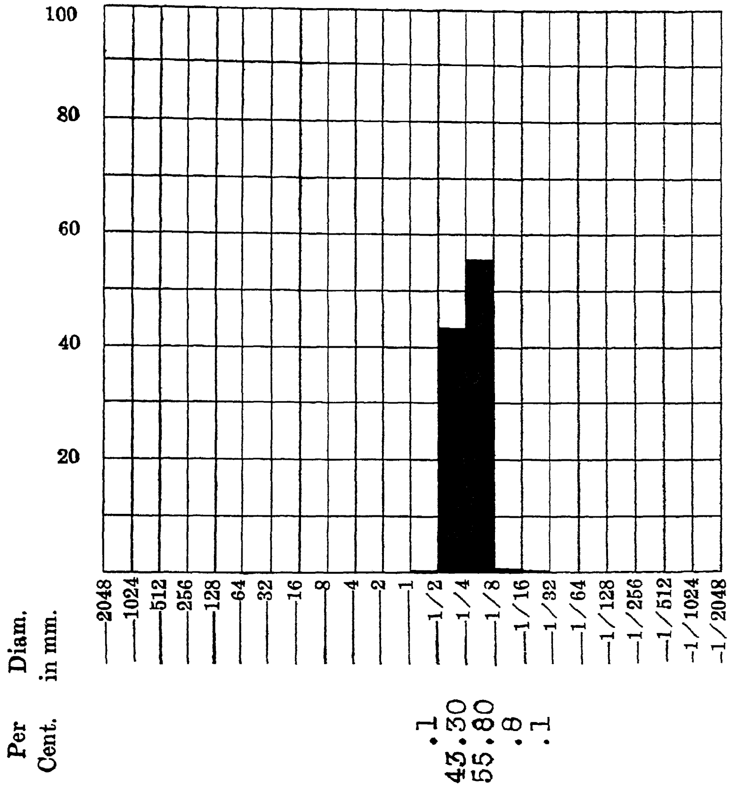

FIG. 22. MECHANICAL COMPOSITION OF DUNE SAND

Analysis by A. C. Trowbridge. Sample collected from top of a dune at Mineral Springs, Indiana, by C. K. Wentworth.

measurement of the roundness of sand grains, certain general facts may be noted. Sand grains are probably on the whole less well rounded than

[81] Dawkins, W. B., The derivation of sand and clay from granite, Geol. Mag., vol. 45, 1908, pp. 466–467.

[82] Ziegler, V., Factors influencing the rounding of sand grains, Jour. Geol., vol. 19, 1911, pp. 645–654; Mackie, W., On the laws that govern the rounding of particles of sand, Trans. Edinburgh Geol. Soc., vol. 7, 1897, p. 298.

small pebbles. The reason for this lies in the cushioning of the grains by the inertia and viscosity of the fluid, and below certain sizes the agents of rounding have little effect. There is probably, then, an optimum size at perhaps the smaller pebble grade where rounding under the influence of these opposing factors is at a maximum.[83] Sand grains which are 50 per cent rounded are seldom found except in oölitic sands, and sand deposits of other origin having this average roundness appear to be extremely rare.

In most sands the roundest grains are neither the largest nor the smallest, but belong to grades just short of the coarsest which are abundant in the deposit. The largest grains are handled by the depositing agent not so freely or generally as somewhat smaller grains, whereas the smaller grains are more effectively cushioned by the air or water. Mackie analysed the factors affecting the rounding of sand grains and expressed the results in instructive algebraic form. He did not, however, evaluate any considerable number of the factors experimentally or by rigorous mathematical treatment, and his results, while perhaps qualitatively correct, are far from having the value even of empirical formulæ in which numerical coefficients are given.[84] Numerous investigations have suggested on theoretical grounds that very small and well rounded sand grains owe their rounding to wind abrasion, and according to Mackie grains less than a fifth of the size of water-rounded grains will be equally well rounded by the wind. Anderson found by experiment under certain conditions that sand grains immersed in water and transported a given distance are worn down to a greater extent than those transported the same distance in air. He also found that the wear is extremely slow and concluded that most rounded spheroidal grains have had a longer history of abrasion than that of a single cycle of transportation and are probably very old geologically.[85] Galloway has investigated the possibility of small grains becoming rounded by solution and believes that this is a factor of geologic importance,[86] and Kindle has pointed out that sand grains may be rounded in the digestive tracts of organisms to smaller dimensions than can be done by water.[87]

[83] Ziegler, V., Factors influencing the rounding of sand grains, Jour. Geol., vol. 19, 1911, pp. 645–654.

[84] Mackie, W., On the laws that govern the rounding of sand, Trans. Edinburgh Geol. Soc., vol. 7, 1897, p. 298.

[85] Anderson, G. E., Experiments on the rate of wear of sand grains, Jour. Geol., vol. 34, 1926, pp. 144–158.

[86] Galloway, J. J., Rounding of sand grains by solution, Am. Jour. Sci., vol. 47, 1919, pp. 270–280.

[87] Kindle, E. M., A neglected factor in the rounding of sand grains, Am. Jour. Sci., vol. 47, 1919, pp. 431–434.

According to Galloway's experiments,[88] if a non-calcareous sand have more than 50 per cent of the grains well rounded, it is of eolian abrasion. If the sand is calcareous, no agent of abrasion is indicated, and such is the case in any sand if the degree of excellent rounding is less than 50 per cent. These experiments also indicated that if the grains of minerals other than quartz were rounded most, water abrasion and deposition are indicated. He further found

that grains of calcite, dolomite, hornblende, and mica, and other soft minerals could be rounded in water at a velocity of 4 miles an hour in 50 to 200 hours to 0.01 mm. and to smaller sizes if the time were lengthened. Below 0.05 mm. in water in that velocity the abrasion was very slow and in 200 hours only a few grains of quartz were round. For calcite a great many grains 0.05 mm. in diameter could be reduced to approximate spheres in less than 50 hours, but grains smaller rounded very slowly, although there were present round grains down to the limit of visibility of the microscope. Also by observation the smallest size in natural, waterworn quartz or calcite sand (from Bermuda and Yukatan) which one could find easily was about 0.05 mm.

This led Galloway to consider

0.05 mm. the lower effective limit for abrasion in water which normally occurs in nature or could easily be produced by experiment. There is, however, no longer theoretical or practical limit to the size of grain which can be abraded to roundness given a sufficient time.

The lower effective limit for wind-blown sands was taken at 0.03 mm.

Organic and oölitic sands have shapes due in part to the forms of organic parts or peculiar to the method of growth of the grains, and in part to subsequent abrasion.

A simple, yet useful, classification of the shapes, which also emphasizes age relations, is that given by Sorby:[89]

1. Normal, angular, fresh-formed sand such as has been derived almost directly from the breaking up of granitic or schistose rocks.
2. Well worn sand in rounded grains, the original angles being completely lost, and the surfaces looking like fine ground glass.
3. Sand mechanically broken into sharp angular chips, showing a glassy fracture.
4. Sand having the grains chemically corroded, so as to produce a peculiar texture of the surface differing from that of worn grains or crystals.
5. Sand in which the grains have a perfectly crystalline outline, in some cases undoubtedly due to the deposition of quartz upon rounded or angular nuclei of ordinary noncrystalline sand.

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[88] Galloway, J. J., Value of the physical characters of sand in the interpretation of the origin of the sandstones, abstract, Bull. Geol. Soc. Am., vol. 33, 1922, p. 104. Private communication, June 29, 1923.

[89] Sorby, H. C., Quart. Jour. Geol. Soc., vol. 36, 1880, p. 58.

Sorby also pointed out the need of distinguishing between the age of the grains and the age of the deposits, and of recognizing grains which have been incorporated in successive sand deposits of different ages.[90] Numerous studies show the exceedingly large amount of wear required to produce the nearly spherical and smoothly rounded pebble and sand grains found in certain formations, and in many instances it seems necessary to postulate abrasive handling during successive geological cycles to explain the final forms, since the lengths of existing rivers or the probable duration of handling on beaches seems quite inadequate.[91]

Closely related to the shapes of sand grains are their surface characteristics.[92] Some show frosted or mat surfaces like the surface of ground glass; others show polished or glassy surfaces or freshly fractured, conchoidal surfaces; while crescentic impact scars mark the surfaces of many grains. Many sands are coated with iron oxide or other cementing material.

Deposits of sand vary widely in their structure details. Marine sands have more uniform and continuous bedding than fluviatile or eolian and usually show less change vertically from stratum to stratum. They are also better sorted than the former. Fluviatile sands occur commonly in lenses and associated with gravels and silts in a rapidly alternating series; and they usually contain considerable percentages of clay and silt. They show a scour and fill or flow and plunge type of bedding. Much instructive detail on the structures of sandstones is contained in a paper by Knight.[93] Eolian sands are usually nearly homogeneous as to size of grain in successive beds and are cross-bedded to a notable degree, the cross-bedding being wind-truncated above and tangent to the horizontal below. Glacial and fluvio-glacial sands usually are well sorted; and if of glacial production, the particles are angular. Residual sands are not assorted, show many solution pits and are of irregular shapes, and are likely to be coated with iron oxide.

The mineralogical composition of sands has been much more extensively studied abroad than in the United States, but such studies are everywhere becoming more numerous and the resulting data are being used with considerable success in the correlation of oil-bearing sands in connection with petroleum exploration.[94] The composition of sands depends on the relative

[90] Sorby, H. C., op. cit., p. 46.

[91] Wentworth, C. K., Sand and gravel resources of the coastal plain of Virginia, Bull. 32, Virginia Geol. Surv., 1930, pp. 100–105.

[92] Sherzer, W. H., Criteria for the recognition of the various types of sand grains, Bull. Geol. Soc. Am., vol. 21, 1910, pp. 625–662.

[93] Knight, S. H., The Fountain and the Casper formations of the Laramie Basin, Univ. Wyoming, Publ. in Sci., Geology, vol. i, no. 1, 1929, pp. 1–82.

[94] Holmes, A., Petrographic methods and calculations, London, 1921, pp. 160–230; Milner, H. B., Sedimentary petrography, 2nd. ed., 1929; Hatch, F. H., and Rastall, R. H., The sedimentary rocks, London, 1913; Boswell, P. G. H., British resources of refractory

proportions of the minerals forming the parent rocks and on the relative durability of these minerals under the controlling conditions of weathering and transportation. One of the most common minerals in igneous and metamorphic rock is quartz, though this mineral is quantitatively subordinate to the feldspars. Because of its superior resistance to both chemical weathering and mechanical attack, quartz is by far the most abundant mineral in sands and sandstones and many such formations are almost wholly composed of quartz grains.

In far-transported sands resulting from mature weathering, grains other than quartz are commonly composed of the more stable minerals of igneous and metamorphic rocks, even though these in many instances are accessory in the original rock and occur only sparingly. In this category are included zircon, rutile, tourmaline, garnet, titanite, cassiterite, andalusite, staurolite, monazite, spinel, and topaz. Magnetite and ilmenite, hornblende, the micas and the feldspars, though progressively less stable, are somewhat prominent in sands owing to the greater abundance with which they occur in the common parent rock.

In sands derived from areas largely underlain by rocks of distinctive mineral composition where weathering is only slightly or moderately advanced, the mineral list may include many of the moderately or only slightly stable minerals, such as the feldspars, microcline, orthoclase, and the soda to lime plagioclases, in the order named, the micas, muscovite or biotite, amphiboles, pyroxenes, feldspathoids, olivine, and many others. Because of the variety of conditions under which minerals weather, and the varying structures of rocks, it is possible to state only an approximate order in which minerals are resistant to weathering. As convenient a statement as any is that by Milner,[95] from which the following table is adapted (table 25).

A number of the minerals which are found most commonly to persist in sands have densities considerably higher than quartz, ranging upward to values nearly twice as great. This physical difference permits a mineral sorting which results in the natural heavy concentrates and is also utilized in

sands, Pt. i, London, 1918, pp. 1-246; Idem., Some aspects of the petrology of sedimentary rocks, Proc. Liverpool Geol. Soc., vol. 13, pt. iv, 1923, pp. 231–303 (A historical review of work on the mineral composition of sedimentary rocks); Ibid., vol. 14, pt. ii, 1925, pp. 164–180; Ibid., vol. 14, pt. iv, 1927, pp. 319–339; Tickel, F. G., Correlative value of the heavy minerals, Bull. Am. Assoc. Pet. Geol., vol. 8, 1924, pp. 158–168; Trowbridge, A. C., and Mortimore, M. E., Correlation of oil sands by sedimentary analysis, Econ. Geol., vol. 20, 1925, pp. 409-425; Reed, R. D., Some methods for heavy mineral investigations, Econ. Geol., vol. 19, 1924, pp. 320–327; Edson, F. C., Heavy mineral work in the Mid Continent region, Rept. Comm. on Sedimentation, Nat. Research Council, 1928–1929, pp. 70–74.

[95] Raeburn, C., and Milner, H. B., Alluvial prospecting, Murby and Sons, London, 1927, p. 71.

carrying out heavy liquid separations in the laboratory for the concentration of small amounts of heavy detrital minerals which are disseminated throughout many sands.

The lodging of coarse gravel on the upper parts of a beach and the segregation of small lenses of heavy mineral grains, magnetite, etc., on the crest of a steeply pitching beach on certain coasts suggest the critical effect of

TABLE 25

	ESSENTIAL ROCK-FORMING MINERALS	ACCESSORY ROCK-FORMING MINERALS
Highly stable	Quartz Calcite (in limestones) Dolomite Gypsum (in clays, etc.)	Zircon Garnet Tourmaline Titanite Corundum Topaz Andalusite Staurolite Rutile Spinel Cassiterite Fluorite Monazite
Less stable	Muscovite Orthoclase, Microline Soda-Lime feldspars	Magnetite Ilmenite
Moderately stable	Monoclinic amphiboles Monoclinic pyroxenes Orthorhombic amphiboles Orthorhombic pyroxenes	
Unstable	Lime-Soda feldspars Felspathoids Olivine Biotite	Pyrite Pyrrhotite Hematite Apatite Glauconite

sudden accelerations by quick wave pulses as opposed to the more steady back-flowing of the wave after it has reached its landward limit. Apparently the larger gravel and the denser but smaller grains are dislodged and carried inland by one type of impulse but are stable against the slower and steadier seaward movement.[96] Among the most common of heavy con-

[96] Barrell, J., Marine and terrestrial conglomerates, Bull. Geol. Soc. Am., vol. 36, 1925, p. 295.

centrates are the black sands which in many instances are composed largely of magnetite grains or of magnetite and ilmenite.[97] The magnetite sands on the north shore of the St. Lawrence near the mouths of the Mingan, Bersimis, Natisquam, Kahushka, and Butiscan rivers are so extensive in places as to have economic importance. They were derived from norite rocks which outcrop along the coast and up the rivers.[98] Similar sands occur on the west coast in California, Oregon, and British Columbia, and still other localities are on the coasts of New Zealand and some of the islands of Japan.[99] Sands with a coating of iron oxide are extremely common in semi-arid regions. Manganese is likely to be present in association with the iron and may take its place. Muscovite is common in moderately transported sands. Biotite is less common, and the ferromagnesian minerals are generally absent or very rare in all sands which have been extensively transported or reworked from residual materials.

Feldspars are only moderately durable, and while usually absent from the larger particles of far-transported sands, they are usually present among the smaller particles. Microcline is the most durable, and the plagioclases the most easily weathered, with orthoclase occupying an intermediate position. Many of the more durable essential or accessory minerals listed above may yield valuable evidence relating to the sources of the sediments. Thus, such minerals as garnet, cassiterite, tourmaline, and topaz suggest pneumatolytic phases of granitic rocks; zircon, rutile, apatite, brookite, hornblende, augite, and the micas, among others, might indicate other igneous rocks. Staurolite, andalusite, sillimanite, epidote, kyanite, and the amphiboles would suggest metamorphic source rocks. Exceptional amounts of ilmenite, rutile, zircon, and tourmaline are believed in many instances to be the result of transmission of these detrital minerals through several generations of sedimentary deposits.[100]

Sands composed of calcium carbonate are supposedly not common, but it seems probable that many limestones were formed from particles of sand dimension. They form both under marine and land conditions, and in the former case they develop where limestone coasts are undergoing erosion and about coral islands. On the coasts of Anticosti, Gotland, and Oesel there are many sand beaches which are largely composed of limestone sands. The softness facilitates rounding, but the easy solubility and the strongly

[97] Wilgus, W. L., and Gunnell, E. M., Minerals from Virginia Coastal plain terrace formations, Washington Univ. Stud., Sci. and Tech. Ser., vol. 5, 1931, pp. 55–68; Shannon, E. V., Mineralogy of some black sands from Idaho, etc., Proc. U. S. Nat. Mus., vol. 60, 1921, pp. 1–33.

[98] Kemp, J. F., School of Mines Quart., vol. 21, 1899, pp. 331–333.

[99] Beck, R., The nature of ore deposits, Trans. by Weed, W. H., 1909, p. 623.

[100] Boswell, P. G. H., British resources of sands and rocks used in glass-making, London, 1918, p. 10.

developed cleavage lead to roughness of surface and fracturing. Sands are occasionally though not commonly composed of gypsum, Herrick[101] describing a gypsum sand area in New Mexico with an extent of about 500 square miles.

Unusual situations occur where sands are developed from limited areas of rock of narrow lithologic range. Thus, in parts of Hawaii the persistent mineral is not quartz, but olivine. Adjacent to some of the Hawaiian pyroclastic craters the sands have olivine as the dominant particle, with augite second in importance, the grains of each being largely bounded by crystal faces.

Detailed estimates of the various organic constituents contained in the reef sand from the Bahamas have been made by Goldman.[102] On volcanic islands composed of rocks of basic composition and on true oceanic islands where only reef formations and the detrital derivatives of calcareous organisms are found, the coarse sediments are formed from the non-quartzose rocks and from a great variety of shells and other organic parts. These tend to be worn down in characteristic fashion, according to the strength and shapes of different parts, and in this way illustrate the same general principles as apply to inorganic pebble material. The various organic materials tend also in some degree to be segregated on beaches and in other places according to the ecological relations of the parent organisms, but very little work has been done on this important question. Descriptions of a number of types of sediment found on oceanic islands have been published recently by Wentworth and Ladd.[103]

Many of the minerals other than quartz, feldspar, and mica which occur in sands show characteristic crystalline forms which facilitate their identification and may by their size and proportions be of some value in tracing the parent formations. Likewise, the shapes of the cavities and inclusions in quartz grains are of considerable importance in such studies.[104]

The deposition of cement around and between the grains of sand converts it into a sandstone. The three principal cementing materials are quartz, limonite, and calcite, important in the order named. Other cements are opal, chalcedony, pyrite, magnetite, hematite, siderite, and magnesium and other carbonates. There is great variation in the extent of cementation.

[101] Herrick, C. L., Geology of the white sands of New Mexico, Jour. Geol., vol. 8, 1900, pp. 112–118.

[102] Goldman, M. I., Proportions of detrital organic calcareous constituents and their chemical alteration in a reef sand from the Bahamas, Carnegie Inst. Washington, Publ. No. 344, 1926, pp. 37–66.

[103] Wentworth, C. K., and Ladd, H. S., Pacific island sediments, Univ. Iowa Studies in Nat. Hist., vol. 13, 1931, pp. 1–47.

[104] Mackie, W., Trans. Edinburgh Geol. Soc., vol. 7, 1896, p. 148.

Some sands are so slightly cemented that they may be pulverized in the hand, while others have been converted into quartzite. Quartz cement is commonly deposited in optical continuity with the crystal structure of the sand grains, so that new particles have regular crystal outlines.[105] The rock may or may not be firm. Numerous structural features and bedding plane markings found in sandstone are described in other sections of this work. An extended treatment of the characters of sandstone has been published by Hadding.[106]

Grit

Grit was originally a provincial term used for coarse-grained sandstones. It has long been used in England by geologists in a similar sense, and also by some for sandstones having sharper and more angular, yet finer, grains than common. Because of this confusion in past usage, it has not been used in the scale of terms adopted here.

Buhrstone

Buhrstone is a siliceous or siliceo-calcareous rock which is used for millstones and other abrasive stones. Geologically it is a fine-grained sandstone of a certain porosity and texture.

Arkose

Arkose[107] is a sedimentary rock composed of material derived from the disintegration of acid igneous rocks of granular texture. There is usually little sorting of the materials. The term is also used by some as an adjective with sandstone or conglomerate to indicate the presence of only slightly weathered products of granitic decay.

The conditions essential for the formation of arkose are: (a) granitic terrane, (b) favorable disintegration conditions accompanied by little decomposition, and (c) conditions of transportation which permit little loss of feldspars. These conditions are best realized in arid regions and regions of low temperature. Of secondary importance are the arkoses formed under conditions of moist and temperate climates.[108] Arkoses may be divided as follows:

[105] Irving, R. D., and Van Hise, C. R., Bull. 8, U. S. Geol. Surv., 1884.

[106] Hadding, A., The Paleozoic sandstones of Sweden, Lunds Universitets Arsskrift, N. F., Avd. 2, Bd. 25, Nr. 3, 1929, pp. 1–287.

[107] Fay, A. H., A glossary of the mining and mineral industry, U. S. Bureau Mines, 1920; Russell, I. C., The Newark system, Bull. 85, U. S. Geol. Surv., pp. 32–35.

[108] Barton, D. C., The geologic significance and genetic classification of arkose deposits, Jour. Geol., vol. 24, 1916, pp. 417–449.

1. Arkoses formed under rigorous climatic conditions. In these, the feldspars show only slight decomposition and the argillaceous material, if present, is small. These develop in (A) desert regions and high (B) latitudes and (C) altitudes.

A. Desert arkoses. The deposits are more or less massively bedded, homogeneous, and not uncommonly of great extent. There is little decomposition, and transportation almost immediately follows disintegration. The colors range from light to reddish. The extent of the deposit depends upon the area of the rock exposed to disintegration, the area of the basin of deposition, and the duration of arid and semi-arid conditions. The deposits may be either terrestrial or marine. If the former, there is likely to be a mixture of materials of eolian and aqueous characteristics, the former having well rounded sand grains, facetted pebbles, local lag gravels, and dune stratification, and the latter the marks of ephemeral and torrential waters. According to Barton, the Torridonian of Scotland, the Sparagmite of Sweden, a part of the lower Old Red Sandstone of Scotland, and the Paysaten arkose (Cretaceous) of British Columbia and Washington are of this origin. Marine arkoses of arid conditions are developed where a desert lies adjacent to the sea. The particles are similar to those of the terrestrial type, but the stratification is more even, due to the fact that marine waters rule in the deposition, and marine fossils may be present. Arkoses of this type are now forming in the Gulf of California.

B. Cold-climate arkoses. The degree of development of granular disintegration in cold climates has not been determined, but block disintegration is extensive. The extent of deposits of arkose in this environment is not known. The colors are grayish.

C. High-altitude arkoses are of small extent. As the elevation makes them but temporary deposits, all of those known are of late geologic age. Lacustrine, landslide, fluviatile, and glacial conditions may participate in the deposition. The colors are likely to be some shade of gray.

2. Arkoses formed directly or indirectly under conditions of moist and usually temperate climatic conditions. Arkoses of this type vary in extent from very small to large. A fine-grained argillaceous matrix is usually present, and the feldspars have undergone a moderate amount of decomposition. They may be either (A) terrestrial or (B) aqueous.

A. Terrestrial arkoses of this origin may be formed under semi-arid conditions and thus be intermediate to those of arid climates, or they may be deposited under moist and chiefly temperate climatic conditions.

In the former the arkose has a reddish color and is composed of subangular, iron-stained grains of quartz and feldspar. The deposits are coarsely stratified, cross-laminated, have much cut-and-fill bedding, mud cracks,

raindrop impressions, and footprints. Barton considers that the Triassic Sugar Loaf arkose of the Connecticut River Valley and the Stockton arkose of New Jersey, New York, and Pennsylvania; the Upper Carboniferous arkose of the Ottweiler of the Rhine Province, and the Rotliegendes of the same region and the Mainz Basin, the Vosges, and the Black Forest; the Old Red Sandstone of England; the arkose of the Cutler (Permian) formation of Colorado and the Fountain (Permian) formation are all of this origin.

In the latter the arkose is grayish and is composed of subangular quartz and considerable decomposed feldspar in a matrix of fine-grained quartz and argillaceous material. These arkoses are commonly carbonaceous and frequently contain fossils of plants. They are arkoses commonly associated with the coal deposits.

B. Marine or lacustrine arkoses. These are formed in shallow waters adjacent to a granite coast that is rapidly being eroded, or near the mouths of rivers which are carrying arkose material. They bear the characteristics of aqueous deposition, and the grains may be fairly well rounded.

3. Lastly are the untransported or sedentary arkoses. These are generally of small extent and grade into the underlying granite.

Greywacke

Greywacke[109] is a variety of sandstone composed of material derived from the disintegration of basic igneous rocks of granular texture, and thus contains abundant grains of biotite, hornblende, magnetite, etc. Thus defined it is the ferromagnesian equivalent of arkose. Greywackes form in the same manner as do arkoses, and find their development under rigorous conditions, either cold or dry and hot. The ready susceptibility to decomposition of the basic minerals probably precludes their extensive development in a region with any considerable degree of moisture.

Greensand

This term is applied to sands which contain a considerable percentage of grains of glauconite. Such sands commonly show little consolidation. The

[109] Fay, A. H., A glossary of the mining and mineral industry, U. S. Bureau Mines, 1920.

Greywacke has also been used in the sense of dark, fragmental rocks composed of argillaceous particles and also for fine-grained sandstones in which there is considerable argillaceous matter. According to Van Hise (A treatise on metamorphism, Mon. 47, U. S. Geol. Surv., 1904, p. 880) a certain degree of metamorphism is implied in the term. Though these latter usages are of long standing, they have for the most part been of rather local usage and have been so irregularly interpreted as scarcely to justify continuance in a modern scheme of terminology. It appears best to adhere to the growing usage expressed in the definition given in the text.

formation of glauconite and the characteristics of glauconite deposits are treated under the heading of iron silicates.

OTHER COARSE CLASTIC ROCKS

Till and Tillite

Till is the name most commonly given to the unstratified drift or boulder clay deposited by glacial ice (fig. 23).[110] The constituent pieces range from the finest clay particles to boulders a hundred or more feet in width and length, and such ranges in size may occur in a single exposure. Much so-called till shows considerable sorting and rude stratification due to partial deposition by water. A rude foliated structure, apparently due to the flowing of fine material around the unyielding masses of the larger boulders, also may occasionally be seen. A mechanical analysis of till is shown in figure 24. Recent studies of glacial sediments including till and fluvio-glacial materials have been reviewed by Leighton.[111]

The rock fragments found in till are the result of two groups of processes. First, the smaller fragments up to coarse sands and many of the larger pieces are angular, broken, practically unabraded rock fragments. Their shapes are controlled by rock structure, mineral and rock cleavages, and the particular agents of disruption. Second, some of the larger fragments and possibly a few of the sand grains have shapes resulting wholly or in part from a very firmly controlled abrasion, giving the glaciated or facetted (soled) pebbles or boulders. In some cases the facets coincide with bedding or fracture planes and appear merely to have been dressed by abrasion, whereas in others they are clearly independent either of the former shape or of the structure of the particles. Where several are present, the lines of junction between them are commonly somewhat broken or rounded. Equally characteristic with the facets are the fine parallel striæ and grooves which are shown on many facetted surfaces. These are commonly best shown on fine-grained, compact limestones.

Glacial striæ differ from those of slickensides in their more individual character, those of the latter being more commonly part of a system of minute fluting, and also in the multiple sets shown by the former. They differ

[110] Woodworth, J. B., The ice contact in the classification of glacial deposits, Am. Geol., vol. 23, 1899, pp. 80–86; Salisbury, R. D., The drift, its characteristics and relationships, Jour. Geol., vol. 2, 1894, pp. 708–724, 837–851; Alden, W. C., and Stebinger, E., Pre-Wisconsin glacial drift in Montana, Bull. Geol. Soc. Am., vol. 24, 1913, pp. 529–572; Alden, W. C., Pleistocene geology of southeastern Wisconsin, Prof. Paper 106, U. S. Geol. Surv., 1918.

[111] Leighton, M. M., Annual report Committee on Sedimentation, Nat. Research Council, 1927–1928, pp. 43–60; 1928–1929, pp. 82–103.

also in that the surfaces on which they are found show no evidence of rock flowage, such as is said to occur on slickensided surfaces.[112]

An attempt has been made by C. D. von Englen to describe in qualitative

FIG. 23. SECTION SHOWING THE MATERIALS OF A MORAINE

A natural section across the terminal moraine (Johnstown), south of Verona, Wisconsin. Photograph by W. H. Twenhofel.

terms the typical shape of glacially modified pebbles.[113] The type form accepted is characterized as flatiron shaped, with many variants. It is

[112] Woodworth, J. B., Bull. Geol. Soc. Am., vol. 23, 1912, pp. 457–462; Lahee, F. H., Field geology, New York, 1916, p. 25.

[113] Von Engeln, O. D., Type form of facetted and striated glacial pebbles, Am. Jour. Sci., vol. 19, 1930, pp. 9–16.

recognized that extensive observations on the part of many students will be required to establish or modify this generalization.

Geologists acquainted with arctic regions have long known that ice jams in high-latitude rivers exert a considerable striating action and produce grooved roundstones and pavements of such stones. Studies by the present writer in the Yukon River Valley not yet published in detail indicate that such action is locally very powerful and that striated and facetted cobbles and boulders are produced which closely resemble those due to glacial action. Considered as a whole, collections of such cobbles differ somewhat from those of glacial origin but it is doubted whether most of the individual cobbles

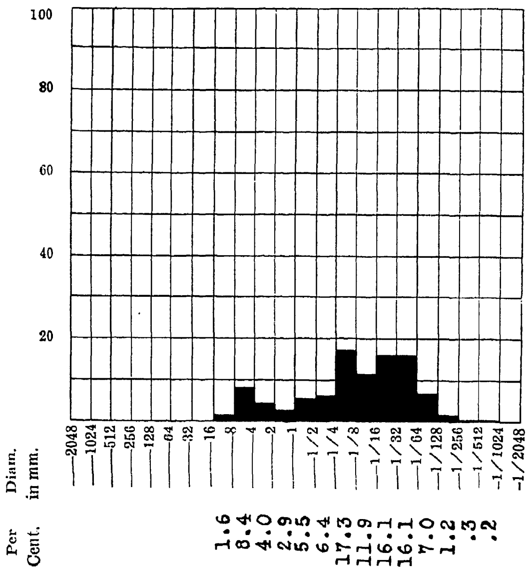

FIG. 24. MECHANICAL COMPOSITION OF TILL
Analysis by J. A. Udden (No. 1). Sample from 6 miles south of La Salle, Illinois

can be identified and it is evident that much caution must be used in the use of such cobbles as criteria of glaciation in some regions.[114]

Glacial débris deposited by water issuing from the ice takes on the characteristics of water-laid sands and gravels, and through ice flotation some particles may be carried long distances beyond the borders of glaciers.

In till composed largely of fine material the boulders lie at random with little order in arrangement; where composed largely of large blocks and boulders, these lie in contact much as in coarse talus, and the fine material

[114] Wentworth, C. K., Striated cobbles in the Southern States, Bull. Geol. Soc. Am., vol. 39, 1928, pp. 941–954.

is in some cases almost wholly absent. Such deposits have been called bear's den moraines.[115] Single boulders are sometimes deposited by ice in delicately balanced fashion on high ledges or on other larger boulders. They also occur in pairs with one leaning against the other in a characteristic fashion or in other delicate arrangements.[116] Boulder pavements consisting of boulders strewn on a surface overridden by glacier ice and striated and polished on their upper surfaces are described by Gilbert [117] as due to local and temporary erosion. They may be covered by till. The name boulder pavement has also been given to the boulder accumulations strewn on a wave-cut terrace where the finer material has been removed. The latter are also produced by river action.[118]

Till is largely composed of fresh, unweathered rock fragments. The finer particles, of sand to clay grade, show in their composition most of the minerals which are found in the larger fragments. In any given region there is usually a preponderance of local rock fragments from a large variety of rocks foreign to the region. Thus, the till of a region of sedimentary rocks is commonly made up largely of fragments of the sedimentary rocks, but may contain fragments of many different kinds of igneous and metamorphic rocks.[119]

In very old till some of the materials may be deeply weathered, and only the quartz, quartzite, and chert fragments be easily recognizable. In general, however, weathering goes on slowly in till because of its impervious character. A peculiar, fine-grained material believed to be the weathered residuum of till has been described as gumbotil.[120]

Most of the known till of the world is of Pleistocene age and is uncemented, but within recent years firmly cemented ancient tills or tillites have been recognized at a number of localities, and more are likely to be discovered in the future.[121] In every other respect these old cemented tills are similar

[115] Tarr, R. S., Glaciation of Mount Katahdin, Maine, Bull. Geol. Soc. Am. vol. 11, 1900, pp. 433–448.

[116] Woodworth, J. B., and Marbut, C. F., The Queen's River moraine in Rhode Island, Jour. Geol., vol. 4, 1896, pp. 691–703.

[117] Gilbert, G. K., Boulder pavement at Wilson, N. Y., Jour. Geol., vol. 6, 1898, pp. 771–775.

[118] Kindle, E. M., Notes on sedimentation in the Mackenzie River basin, Jour. Geol., vol. 26, 1918, pp. 341–360.

[119] Crosby, W. O., Proc. Boston Soc. Nat. Hist., vol. 25, 1890, pp. 115–172.

[120] Kay, G. F., and Pearce, J. N., The origin of gumbotil, Jour. Geol., vol. 28, 1920, pp. 89–125.

[121] Coleman, A. P., The Lower Huronian ice age, Jour. Geol., vol. 16, 1908, pp. 149–158; Davis, W. M., Observations in South Africa, Bull. Geol. Soc. Am., vol. 17, 1906, pp. 401–420, pls. 50–54; Mellor, E. T., The glacial (Dwika) conglomerate of South Africa, Am. Jour. Sci., vol. 20, 1905, pp. 107–118; Idem., Quart. Jour. Geol. Soc., vol. 61, 1905, pp. 679–689; Howchin, W., Glacial beds of the Cambrian age in South Australia, Quart. Jour. Geol. Soc., vol. 64, 1908, pp. 234–259; Coleman, A. P., Ice ages, recent and ancient, New York, 1926.

to those of Pleistocene age. Associated with the unstratified drift or till in glaciated regions are stratified sands and gravels which do not differ materially from other stream-laid deposits.

Talus Breccia and Related Rocks

Breccia is a fragmental secondary rock in which the fragments are angular. Rocks of a great variety of origins have been included under this term and described at considerable length by Norton,[122] whose classification is valuable as a collection of the names of all possible variants of this sort of rock, but many of the rocks described are included under other headings by most writers. Further description and enumeration of the types of breccias, both sedimentary and tectonic, has been presented by Reynolds.[123]

FIG. 25. SLOPE WASH, WEATHERED DETRITUS STREWN ON STEEP SLOPE WITH LITTLE SORTING OR STRATIFICATION

Conduit road near Great Falls, Maryland. Photograph by C. K. Wentworth, U. S. Geol. Surv.

Most important probably of all breccias is that formed through the action of gravity as talus at the base of cliffs. It grades into rain or slope wash material on its lower margin. Coarse talus mantling mountain slopes is known in England as scree material. Angular blocks accumulated at the base of a sea cliff form a sea-cliff breccia if they are not sufficiently rounded to be called a conglomerate. Such a breccia must from the nature of the case be of extremely limited extent.

[122] Norton, W. H., A classification of breccias, Jour. Geol., vol. 25, 1917, pp. 160–194.
[123] Reynolds, S. H., Breccias, Geol. Mag., vol. 65, 1928, pp. 97–107.

The constituent pieces in talus have a wide range of dimension and shape and are mingled with little reference to size.[124] Where rock breaking is dominant, talus is coarse; where decomposition is more important, talus is finer in average grain. When such material is of gravel grade, it is sometimes known as rubble (figs. 25 and 26).

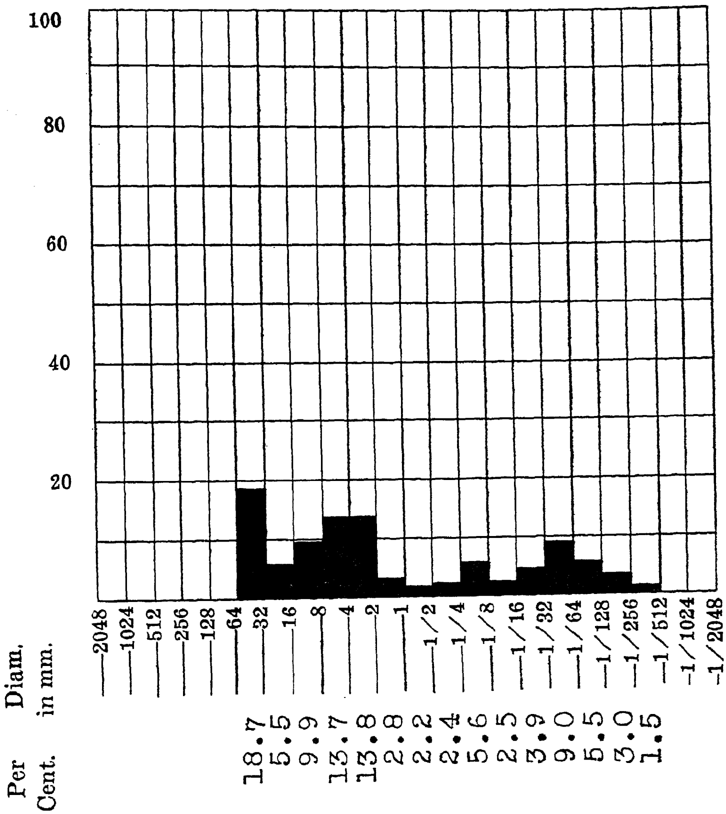

FIG. 26. MECHANICAL COMPOSITION OF RAIN-WASHED SLOPE DETRITUS
Analysis by C. K. Wentworth (No. 10760). Sample from cut on Conduit Road near Great Falls, Maryland.

Talus rarely shows real bedding. In case the fragments are flat or elongate, they may lie and slide with their longer diameters parallel to the angle of rest and thus simulate a bedded structure, and sliding of fine-grained talus may also give a rude appearance of bedding. The mineral constitution of

[124] Reynolds, D. D., and Leavitt, D. H., A scree of Triassic age, Am. Jour. Sci., vol. 13, 1927, pp. 167–171.

talus is that of the parent rock, except as it has been modified by decomposition. Talus formations are wedge-shaped in transverse section and limited to a few hundreds of feet in width, though they may be a score or more of miles in length.

Certain other types of accumulations, as rock glaciers, mud-flows, and landslide deposits, are related to talus.[125] These differ genetically from true talus formations in that the débris is transported to greater distances from its sources.

Bajada accumulations at the foot of mountain slopes are called breccias by some and conglomerates by others. They are formed in arid regions where great quantities of rock and sand with water and mud flow as a thick stream down mountain sides. Slight rounding and imperfect sorting are characteristic. A detailed description of a formation probably of this general type and a discussion of the related group of genetic processes are presented by Woodford.[126]

Desiccation breccia is formed by the drying and cracking of mud or clay and the incorporation of the unrounded fragments in the next sedimentary stratum. Glide breccias are produced by the breaking up of newly formed beds through gliding on the sea floor.

Tectonic breccias or autoclastics of various sorts are beyond the scope of this discussion.

Residual Breccia

This is an accumulation of the larger angular fragments of the mantle rock. It is a result of concentration, the finer materials having been removed by water or wind. Such are the surface accumulations of stones known as gibbers in the Australian deserts, where disruption of the rock is largely due to "sun flaking" under extreme temperature changes.[127] Stones which are residual on sand plains or deserts may be abraded to facetted forms and are variously known as sand-blasted pebbles, dreikanter, einkanter, and glyptoliths.[128] Where the material is heterogeneous, the peb-

[125] Ramsey, A. C., and Geikie, J., The geology of Gibraltar, Quart. Jour. Geol. Soc., vol. 34, 1878, pp. 505–541; Capps, S. R., jr., Rock glaciers in Alaska, Jour. Geol., vol. 18, 1910, pp. 359–375; Blackwelder, E., Mudflow as a geologic agent in semi-arid mountains, Bull. Geol. Soc. Am., vol. 39, 1928, pp. 465–484.

[126] Woodford, A. O., The San Onofre breccia, Univ. California Publ., Bull. Dept. Geol. Sci., vol. 15, no. 7, 1925, pp. 159–280.

[127] Howchin, W., The geology of South Australia, Adelaide, 1918, pp. 60, 134.

[128] Woodworth, J. B., Postglacial eolian action in southern New England, Am. Jour. Sci., vol. 47, 1894, pp. 63–71; Discussions, Geol. Mag., vol. 47, 1911, pp. 85, 239, 282, 477; use of term dreikanter; Bryan, K., Windworn stones or ventifacts: a discussion and bibliography, Rept. Committee on Sedimentation, Nat. Research Council, Reprint and Circular Ser., no. 98, 1931, pp. 29–50.

bles become etched differentially, and, if of hard material, highly polished.[129] Residual chert breccias of large extent accumulate over limestone or chalk formations as a consequence of the removal of the carbonate in solution. Extensive accumulations exist over the Flint Hills of central Kansas, portions of the Edwards Plateau of Texas, and many other places.

Slope-washed material such as that shown in figure 25 is composed of angular fragments of local material rudely assorted and stratified by surface water. It is transitional between talus and piedmont alluvial material.

The Coarse Pyroclastics

These are found near the volcanoes which ejected them and accumulate either by gravity alone or by aqueous or eolian transportation, the coarser particles settling closer to the point of origin. They consist of "volcanic sand," still coarser pieces or lapilli, and the still larger "bombs." The lapilli and "bombs" may be rounded, pear-shaped, or oblately spheroid from the rotary motion which accompanies their expulsion.[130]

"Bombs" up to 5 or 6 meters in diameter have been observed. Some large volcanic ejecta are long, irregular, and sprawling in shape. They seem to be formed by the slinging of rope-like masses in explosions or by subsequent spattering as larger "bombs" strike the earth. All these coarser materials are more or less porous from the presence of included gases at the time of cooling.

By the accumulations of such materials, thick deposits are formed adjacent to the volcanic vent, which become thinner at greater distances. The coarser material becomes by cementation a volcanic breccia; the finer material, formed of lapilli or "volcanic sand" cemented together, is known as tuff, which name is also applied to the cemented ash. Cementation proceeds as a rule rather rapidly, because of the susceptibility of the freshly exposed material to leaching and infiltration into lower layers of the leached material. When the coarser materials are worked over by rivers or waves before their final deposition, they become more rounded and form gravels or conglomerates of volcanic constituents.

The character of the bedding of these rocks varies with conditions, that close to the source being rude, while that farther out in the realm of the finer pyroclastic material is more perfect. The mineral composition depends mainly on the composition of the parent lava. In addition to the lava

[129] Wade, A., Some observations on the eastern desert of Egypt, Quart. Jour. Geol. Soc., vol. 67, 1911, pp. 238–262.

[130] Russell, I. C., Geology and water resources of the Snake River plains of Idaho, Bull. 199, U. S. Geol. Surv., 1902, pp. 72–80; Wentworth, C. K., Pyroclastic geology of Oahu, Bull. 30, Bishop Museum, 1926, pp. 1–121.

derivatives, there are also in some cases considerable quantities of the country rock or of more ancient volcanic rock blown out as fragments from the volcanic vent. Volcanic fragments of other than exposed origin, such as fragments of solidified lavas and pillows from pillow lavas,[131] are not uncommon in these rocks and may even dominate. Study of pyroclastic craters of the Island of Oahu, Hawaii, emphasizes the enormous preponderance in such deposits of "bombs" which are merely broken blocks of older lava rather than twisted or spun masses of new lava, though the latter are known. In the 1924 explosive eruption at Kilauea not a particle of new lava was blown out, the detritus consisting wholly of comminuted rock from the walls of the vent.[132]

The structure of pyroclastic rocks contains many characteristic elements close to the craters where the accumulation taken place rapidly and directly from the air. These include synclines and anticlines of deposition, where the ash is mantled on the irregularities of existing topography, and saucer-shaped depressions of the bedding, where large bombs land on the newly fallen ash. When much water is involved and at situations more remote from the vent where ordinary types of sedimentation dominate, the structures become those more common to such situations.

All gradations exist between the somewhat broken and slightly disturbed fragments of lava and the farther-transported and better-sorted lava derivatives which enter into a true sedimentary rock. The materials in all these cases are so similar and the rocks are so intermingled structurally, that it is a matter of great difficulty at times to distinguish between the lava and the volcanic breccia or tuff, especially since the lava not infrequently in its flow and pillow structures simulates the breccia structure in a most confusing fashion.

The Finer-grained Clastic Sediments

Under this heading are included those sedimentary rocks of mechanical deposition of which the particles are less than 1/16 mm. in diameter. They are divided into a coarser and a finer group, of which the separating dimension has been placed at 1/256 mm., or about 4 μ. To the former the name *silt* has been applied, and to the latter, *clay*. This definition of clay places the limiting dimension at a somewhat larger figure than has been done by Hall[133] and Odén,[134] in whose papers it has been defined as "such a

[131] MacKay, B. R., Beauceville map-area, Geol. Surv. Canada, Mem. 127, 1921, p. 23.

[132] Jaggar, T. A., and Finch, R. H., Explosive eruption of Kilauea, Am. Jour. Sci., vol. 8, 1924, pp. 353–374.

[133] Hall, A. D., The Soil, London, 1912, pp. 34–39.

[134] Odén, S., Allgemeine Einleitung zur Chemie und physikalischen Chemie der Tone, Bull. Geol. Inst., Upsala, vol. 15, 1916, pp. 176–177.

dispersed structure of mineral fragments in which there predominate parts smaller than 2μ," a limiting dimension about one-half of that used here. Cartwright[135] places the limiting dimensions of silt at 0.05 and 0.005 mm., and those of clay below the latter figure. Many clay particles are, in fact, of colloidal dimensions.

The indurated equivalents of silt and clay are siltstones and claystones. The general name of shale has been applied to indurated clays and silts, and together both are not infrequently designated as clay. The term, *shale*, has been defined by some students as those lithified clays and silts possessing cleavage parallel to bedding, but without development of mica. This definition fails in being both too exclusive and too inclusive. There are siltstones and claystones without cleavage which should be designated shales, and there are anamorphosed equivalents of these which show no macroscopic development of mica, but have secondary cleavage. These are slates, the development of secondary cleavage in the latter being the chief differentiating character. The change from clay to shale is attended by a greater or less degree of recrystallization of the constituents and usually some enlargement of particles. This recrystallization probably begins shortly after deposition, and in all likelihood continues indefinitely. Dry shales on being wetted retain coherence; dry clays, not containing oil, on being similarly treated slack and fall apart.

Silts are largely composed of rock dust and flour which have been produced by rock abrasion, grinding, and impact, and with these are particles of resistant minerals which have been released through the decomposition of the surrounding materials. Clays are composed of the very fine particles resulting from abrasion, grinding, and impact, and the minute mineral particles produced in rock decomposition. The major constituents are hydrous aluminum silicates, silicon dioxide, and ferric and aluminum oxides and hydroxides. Ashley[136] defines clay as a mixture of "minerals of which the representative members are silicates of aluminum, iron, the alkalies, and the alkaline earths. The hydrated silicate of aluminum, kaolin ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$), is the most characteristic of these. Some feldspar is usually present." Terzaghi[137] states that "clay represents a mixture of very minute bulky and scale-like particles held together by films of solidified water acting as a glue," the scale-like particles in Norwegian clays consisting of "chlorite, talcum, muscovite, and biotite," representing "about 12 per cent to 27.7

[135] Cartwright, L. D., jr., Sedimentation of the Pico formation in the Ventura Quadrangle, California, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, p. 462.

[136] Ashley, H. E., The colloid matter of clay and its measurement, Bull. 388, U. S. Geol. Surv., 1909, p. 7.

[137] Terzaghi, C., The physical properties of clay, Tech. Engineering News, vol. 9, 1928, pp. 10–11, 36.

per cent of the total weight." The water is considered solid because of its being held in sub-capillary spaces. The plasticity of clay is ascribed to the scale-like particles, a view supported by the fact that powdered mica, chlorite, and other micaceous minerals have plasticity equal or similar to that of heavy clay.

The constituents of clays and silts which are due to abrasion, grinding, and impact may be anything; they usually are the most common rock-making minerals, as quartz, feldspar, etc. Other constituents are the clay minerals, various zeolites, variable quantities of carbonates and sulphates, and equally variable quantities of organic matter. Some of the minerals probably were formed in the clays from materials present from deposition; other were precipitated from solution or suspension. There are all gradations between clays and silts and between each of them and the coarser clastics, and there are few deposits of either which are composed of a single substance.

Knowledge of the clay minerals is more or less incomplete and there is much difficulty involved in their study, due to the small dimensions of the particles and the rare occurrences of pure material. Nearly all are hydrated silicates of aluminum, the ratio of silica to alumina not being subject to wide variation. According to Ross and Kerr[138], four groups of clay minerals have been recognized, as follows: (1) the kaolin group, (2) the montmorillonite-beidellite group, (3) the potash-bearing clays, and (4) a group occurring in many clays whose properties have not been definitely determined.

The kaolin group seems to have three distinct minerals; kaolinite, dickite, and nacrite, and two others, halloysite and allophane, whose distinctions from the others do not seem to be clear. Kaolinite is the common mineral of most residual and deposited clays, and it and halloysite result from the mature weathering of aluminous rocks, commonly granites and pegmatites. Kaolinite forms locally beneath swamps where leaching by organic acids takes place, and it is associated with ore deposits where aluminous rocks have been acted on by sulphuric acid produced by the oxidation of sulphides. It is the most important mineral with which the sedimentationist is concerned. Nacrite is rare and so far as known seems to be associated with hypogene alteration. Dickite has been most commonly reported in association with metallic minerals and seems usually to occur in small quantities, the only large body reported being in a district of Chihuahua, Mexico. Hydrothermal alteration seems to be responsible for most occurrences. The mineral halloysite is widespread and makes up parts of many kaolin

[138] Ross, C. S., and Kerr, P. F., The clay minerals, Prof. Paper 165-E, U. S. Geol. Surv., 1931; The clay minerals and their identity, Jour. Sed. Pet., vol. 1, 1931, pp. 55–64.

deposits. Ross and Kerr interpret it as differing from kaolinite principally in the fine state of division of the mineral particles, and they state that its X-ray pattern indicates that it is sub-microscopically crystalline kaolinite. Allophane seems to be amorphous and to differ from kaolinite in containing less silica and more water.

The montmorillonite-beidellite group has wide distribution and its five members are found in many sedimentary rocks. These members seem to be completely isomorphous. Their compositions are approximately as follows:

$H_2O + H_2O$	$Al_2O_3 \cdot 2SiO_2 + Aq$
$H_2O + H_2O$	$Al_2O_3 \cdot 3SiO_2 + Aq$ Beidellite
$H_2O + H_2O$	$Fe_2O_3 \cdot 3SiO_2 + Aq$ Nontronite
$H_2O + H_2O$ (MgO, CaO, etc.)	$Al_2O_3 \cdot 5SiO_2 + Aq$ Montmorillonite
$H_2O + H_2O$ $9MgO$	$Al_2O_3 \cdot 9SiO_2 + Aq$ Saponite

The first member has the composition of kaolinite, from which it differs in other properties. Beidellite commonly contains ferric iron. A clay mineral of the beidellite type is common in many marine shales, the soils of the cooler and more moist portions of a country, and the soils of arid regions where leaching is not profound. The clay mineral in the bentonites of the Upper Cretaceous of Arkansas, Oklahoma, and Texas is beidellite. A few clay beds are known that contain both kaolinite and beidellite. This may have arisen from the kaolinization of a part of the beidellite or from deposition of kaolinite and beidellite derived from different terranes or different regions. The clay mineral of most bentonites is montmorillonite or a closely related mineral. The normal alteration of latitic volcanic glasses or ash produces montmorillonite-beidellite minerals, and the alteration of ferromagnesian minerals seems to produce clay minerals of this group more readily than does the alteration of feldspars. However, montmorillonite and beidellite produced from the alteration of feldspar are known and the former is a partial constituent of fullers earth from southern Georgia and Florida.

The potash-bearing clays are less well known, but they form some part of many soils and possibly shales. Their most widespread occurrence is in the meta-bentonites of the upper Mississippi Valley, Ontario, and the Appalachian region. The conditions necessary for their formation are not well understood.

Table 26 gives Marshall's[139] classification of the clay minerals.

As a consequence of the extreme fineness of the particles composing clays and silts, there is a tremendous surface present in a small volume of the

[139] Marshall, C. E., Clays as minerals and colloids, Trans. Ceramic Soc., vol. 30, 1931, pp. 81–97. It will be noticed that there does not seem to be complete agreement between Marshall, and Ross and Kerr. The differences, however, seem trivial.

material, Mitscherlich estimating that a gram of clay might have from 200 to 900 square meters of surface,[140] figures which Odén considers may be excessive.[141] This great surface permits great adsorption of other substances, the common presence of potash being thus explained by some students. Clays resulting from rock decomposition and undergoing extensive leaching are low in calcium, sodium, and magnesium, but are apt to have a higher potassium-sodium ratio than the rocks from which they were derived; whereas clays and silts resulting from rock impact, grinding, and abrasion

TABLE 26

CLAY MINERALS

Containing Al_2O_3 and SiO_2 Intermediate series Containing Fe_2O_3 and SiO_2

Showing base exchange data No base exchange data Chloropal, Nontronite ($Fe_2O_3 \cdot 3SiO_2 \cdot 2H_2O$) ($Fe_2O_3 \cdot 8SiO_2 \cdot (Ca \cdot Mg)O \cdot 7H_2O$)

Montmorillonite Potash-bearing clays

Schrotterite ($8Al_2O_3 \cdot 3SiO_2 \cdot 30H_2O$) Kaolins ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) Newtonite ($Al_2O_3 \cdot 2SiO_2 \cdot 5H_2O$)

Allophane ($Al_2O_3 \cdot SiO_2 \cdot 5H_2O$) Halloysite ($Al_2O_3 \cdot 2SiO_2 \cdot 7H_2O$) Beidellite Leverrierite ($Al_2O_3 \cdot 3SiO_2 \cdot 3H_2O$)

Cimolite ($2Al_2O_3 \cdot 9SiO_2 \cdot 6H_2O$) Pyrophilite ($Al_2O_3 \cdot 4SiO_2 \cdot H_2O$)

Dickite Nacrite Kaolinite

may be high in the carbonates and other more or less soluble constituents. In clays of the latter origin the potassium-sodium ratio is apt to be lower than in clays of residual origin. The alumina content of leached clays seems to be higher than obtains for unleached clays.[142]

The particles composing clays and silts are little rounded, except as rounding results from solution or abrasion within the intestinal tracts of

[140] Mitscherlich, E. A., Bodenskunde, Berlin, 1913, p. 70.

[141] Odén, S., op. cit., p. 178.

[142] Ross, D. W., Nature and origin of refractory clays, Jour. Am. Ceramic Soc., vol. 10, 1929, p. 709.

organisms. The smallness of the particles makes it possible for them to be transported in currents of low competency, thus leading to deposition in waters of greater depth or greater quietness than the coarser clastics.

Mechanical analyses of a clay or silt state very little with respect to properties, and two clays or silts of widely different characteristics may be composed of particles of very similar dimensions. On the other hand, chemical analyses give few data with respect to other characteristics, and two clays or silts of essentially the same composition may be physically unlike. These substances are not described until mineralogical, chemical, and mechanical constitutions are given.

On the basis of constituents, clays and silts and their indurated equivalents have been described as argillaceous, siliceous, arenaceous, ferruginous, glauconitic, gypsiferous, volcanic, carbonaceous, and bituminous. Each of the constituents which gives the product its name is likely to be present to some degree in any clay or silt. A clay with sufficient organic matter to reduce the iron might contain more iron than one designated ferruginous, so that the classification fails in exactness and is somewhat difficult of application. These substances have also been classified on the basis of color, but this is little more than a reflection of the characters of the constituents. A classification on the basis of the processes and environments responsible for deposition seems to be the most satisfactory from the geologic point of view, but labors under the disadvantage that essential identity of material may occur in several environments. On this basis it is possible to differentiate seven different varieties of clays and silts, as follows: residual, glacial, fluvial, lacustrine, marine, volcanic, and eolian. These are considered in the order listed.

RESIDUAL CLAYS AND SILTS

Residual clays and silts are not sorted and may contain small to large particles of the undecomposed mother rocks, these particles generally not having yielded to decay because of greater resistance; some form of quartz, as chert, is common. The prevailing colors of residual products in warm humid regions with good underground drainage are reds, browns, or yellows, due to oxidation and hydration of the iron content. In cooler regions with good drainage the colors tend to be gray to white. These are the *podsols* of the pedologists and the colors are due to iron removal. Semi-arid and arid regions tend to have light-colored clays and silts. Residual clays and silts are usually low in calcium, magnesium, and sodium, and, after prolonged leaching, in potash; but this generalization may not hold in semi-arid and arid regions, as some of their clays and silts contain much soluble matter. Although residual clays and silts are abundant on the present land surface, they do not seem to be common in the geologic column.

Analyses of some residual clays are given in table 27.

In tropical and sub-tropical regions with good underground drainage there is no frost action to destroy the porosity of the clay products resulting from rock decomposition, and decomposition proceeds farther than is usually the case in regions where frost prevails. The result is a more complete decomposition of silicates, and residual products consist essentially of ferric and aluminum oxides and hydroxides and free silica, the proportions varying with localities and the rocks from which the residual materials were derived. The product is laterite[143] or bauxite. Due to contained iron, these have colors which are shades of red to brown. Laterite is known to have been derived from granite, gneiss, volcanic ash, basalt, diorite, and other rocks. Analyses showing variations in composition are given in table 28.[144] In

TABLE 27

	1*	2	3	4
	per cent	*per cent*	*per cent*	*per cent*
SiO_2	55.90	55.42	71.13	49.59
Al_2O_3	19.92	22.17	12.50	18.64
Fe_2O_3	7.30	8.30	5.52	17.19
FeO	0.39	Trace	0.45	0.27
MgO	1.18	1.45	0.38	0.73
CaO	0.50	0.15	0.85	0.93
MnO			0.04	0.01
Na_2O	0.23	0.17	2.19	0.80
K_2O	4.79	2.32	1.61	0.93
H_2O	9.06	9.86	4.63	10.46
TiO_2	0.20		0.45	0.28
P_2O_5	0.10		0.02	0.03
CO_2	0.38		0.43	0.30
Organic C			0.19	0.34
	99.95	99.84	100.39	100.50

* 1. Residual clay from limestone, Staunton, Va., analysis by Geo. Steiger, U. S. Geol. Surv., Clarke, F. W., Bull. 770, U. S. Geol. Surv., 1924, p. 511.

2. Residual clay from Knox dolomite, Morrisville, Ala., analysis by W. F. Hillebrand. Russell, I. C., Bull. 52, U. S. Geol. Surv., 1889, p. 251.

3. Residual clay from dolomite, Dodgeville, Wis., 4½ feet beneath the surface, dried at 100°.

4. As number 3, but 8½ feet beneath the surface. Both 3 and 4 from Clarke, F. W., op. cit., p. 512.

[143] Known as Cabook on the Island of Ceylon. See Glinka, K. D., The great soil groups of the world and their development, Transl. by Marbut, C. F., 1928, p. 46.

[144] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 496–504.

the main, laterite and bauxite appear to be residual deposits, but it is possible that they may originate in other ways,[145] as suggested by Campbell[146] and Simpson.[147] Some laterite and bauxite may have been transported and deposited by streams. Such would be likely to contain material which has undergone a lesser extent of weathering. The subject is further considered in connection with the iron-bearing sediments.

TABLE 28

	GRANITE LATERITE	DIORITE LATERITE
	per cent	*per cent*
SiO_2	52.06	3.88
Al_2O_3	29.49	49.89
Fe_2O_3	4.64	20.11
H_2O	14.40	25.98

GLACIAL CLAYS AND SILTS

Glacial clays and silts contain large quantities of materials which result from rock grinding and abrasion, but they may also contain considerable quantities of products of rock decomposition. The former appear to dominate in the clays and silts of existing mountain glaciers, but the clays and silts deposited during continental glaciation must have contained the soil which had previously mantled the surfaces. These decomposed products should be most important in the terminal morainal deposits and less common in the recessional moraines. Silts and clays of glacial deposition usually are light colored. Where they occur in moraines and are the result of ice deposition, sorting is poor, but where deposited by melt waters, sorting may be very good. Except for sorting, the aqueo-glacial clays and silts are similar to the unsorted forms. As the composition of glacial clays and silts depends very greatly on the character of the rock from which they were derived, they do not have nearly so homogeneous a composition as do residual clays. The calcium and magnesian content may be high, and the potassium-sodium ratio relatively low, but the character of the contributing rocks and soils largely controls results. Some analyses are given in table 29.

[145] Oldham, R. D., Manual of the geology of India, 2nd ed., 1893, pp. 348–370; and Lake, P., Mem. Geol. Surv., India, vol. 24, pt. iii, 1890, pp. 17–46, for theories of formation.

[146] Campbell, J. M., Trans. Inst. Min. and Met., vol. 19, 1910, p. 432; Laterite, its origin, structure, and minerals, Mining Mag., vol. 17, 1917, p. 178.

[147] Simpson, K. S., Notes on laterites in western Australia, Geol. Mag., vol. 49, 1912, p. 405.

FLUVIAL CLAYS AND SILTS

Fluvial clays and silts are usually not well sorted and contain considerable quantities of sand. Organic matter is also very commonly present. Beds are rarely continuous and may change to sands or gravels within short distances. The sediments may contain considerable soluble material in the form of carbonates and sulphates, and in humid districts the potassium-sodium ratio may be relatively high. A high carbonate and sulphate content

TABLE 29

	1*	2
	per cent	*per cent*
SiO_2	48.81	74.89
Al_2O_3	7.54	12.22
Fe_2O_3	2.53	
FeO	0.65	4.29
MgO	7.05	0.07
CaO	11.83	1.58
MnO	0.03	0.17
Na_2O	0.92	1.06
K_2O	2.60	2.64
H_2O	2.02	3.21†
TiO_2	0.45	
CO_2	15.47	
P_2O_5	0.13	0.07
SO_3	0.05	
Cl	0.04	
Organic C	0.38	
	100.50	100.20

* 1. Glacial clay from Milwaukee, dried at 100°. Chamberlin, T. C., and Salisbury, R. D., Sixth Ann. Rept., U. S. Geol. Surv., 1885, p. 578.

2. Glacial clay from Scotland. Mackie, W., Trans. Edinburgh Geol. Soc., vol. 8, 1901, p. 60.

† Equals loss on ignition.

is characteristic of the clays and silts deposited on dry and semi-arid regions. Colors may be anything. In regions with both uplands and flood plains covered with much vegetation, colors tend to be dark; the clays and silts deposited on dry and semi-arid flood plains by streams rising in well drained moist and warm upland regions are apt to have red and brown colors. Regions of less warmth and moisture contribute yellow to gray silts and clays to dry to semi-arid flood plains. Clays and silts of fluvial deposition in arid to semi-arid regions may contain more or less disseminated, syngenetic

gypsum, a feature, however, not confined to fluvial clays and silts. Analyses of the fluvial clays and silts of flood plains are given in table 30.

LACUSTRINE CLAYS AND SILTS

Lacustrine clays and silts may be expected to be well sorted, particularly in the deposits distant from shore influence. More or less carbonaceous and other organic matter will probably be present, except in the deposits of those lakes whose waters are very cold. There may be a considerable calcareous content in the clays and silts of lakes whose waters are not permanently cold, and the clays and silts may grade into marls. Lamination may or may not be present, the latter seemingly less likely in lakes with warm waters. Stratification is fairly continuous. Clays may be expected

TABLE 30

	1*	2
	per cent	*per cent*
SiO_2	69.96	45.10
Al_2O_3	10.52	15.95
Fe_2O_3 / FeO	3.47	13.25 (Fe_2O_3)
MgO	1.41	2.64
CaO	2.17	4.85
MnO	0.06	
Na_2O	1.51	0.85
K_2O	2.30	1.95
H_2O^-	3.78	6.70
H_2O^+	1.96	8.84†
TiO_2	0.59	
CO_2	1.40	
P_2O_5	0.18	
SO_3	0.03	0.34
Cl	0.30	
Organic matter	0.66	
Misc	0.3229	
	100.6229	
Less O	0.12	
	100.5029	100.47

* 1. Analysis of a composite of 235 samples, collected by E. W. Shaw in the delta of the Mississippi. Analyzed by G. Steiger, Jour. Wash. Acad. Sci., vol. 4, 1914, p. 59.

2. Analysis of Nile mud. Analysis by C. v. John, Verhandl. k.-k. geol. Reichsanstalt, 1896, p. 259. See Clarke, F. W., op. cit., 1924, pp. 508–509.

† Probably includes alkalies.

to occur in the central part of deep lake basins, and the silts shoreward. The distribution is complicated by the conditions permitting the formation of marl. There is great variation in different lakes consequent to shore topography, depth, dimension, rainfall, temperature, and other factors. Analyses[148] of lake clays from Lake Ontario are given in table 31. The lower lime and magnesia content of the deeper waters is noteworthy and important.

MARINE CLAYS AND SILTS

Marine clays and silts tend to be well sorted, with the stratification planes ranging in distances apart from almost the thinness of paper to many feet.

TABLE 31

	1*	2
	per cent	*per cent*
SiO_2	57.42	59.18
Al_2O_3	12.91	17.30
Fe_2O_3 (iron so expressed)	4.85	6.80
CaO	7.60	1.16
MgO	3.23	2.31
Ignition	9.00	8.46
Alkalies	Not determined	Not determined
	95.01	95.21

* 1. Nine shales north of Fair Haven, N. Y., depth 372 feet, color grayish yellow, 69 per cent passes 200 mesh screen, low plasticity.

2. Lake bottom northwest of Oswego, N. Y., depth 630 feet, alternating bands of black and grayish buff, very fine.

Colors may be anything, but red is not common. The characteristics and composition depend upon the kinds of the rock of the adjacent land, the region drained by the streams emptying into the sea, the distance from the shore and mouths of streams, the depth of water, the extent of water circulation, the temperature, and other factors.

Marine clays and silts are of two general classes. One includes those clays and silts derived directly from the land and deposited by streams and marine currents, the sediments being brought to the sea by rivers, or eroded by waves from the shore. They were precipitated either because of the checking of current velocity or the flocculation of fine particles by colloids of opposite sign or by electrolytes in solution. The deposits are relatively

[148] Kindle, E. M., The bottom deposits of Lake Ontario, Proc. and Trans. Roy. Soc. Canada, vol. 19, sec. 4, 1925, p. 56.

close to the shore and constitute the red, blue, black, green, and other colored muds. The other class was derived from fine particles long held in suspension, material dropped from the atmosphere, decomposition of volcanic and suspended matter, and the residue following solution of matter of organic origin. This class is represented by the red clay of the deep abyss.

Red Muds

Certain parts of the ocean bottom adjacent to the mouths of tropical rivers are covered with reddish brown muds, the color being due to contained ferric oxide or hydroxide. Ferrous sulphide and glauconite, common in some marine clays, are absent or very rare. Although the colors are reddish, the chemical composition does not greatly differ from that of the blue and green muds deposited in the same general regions. The lime content ranges from 6 to 60 per cent and some free silicon dioxide is generally present. These muds usually contain a few frustules of diatoms and spicules of siliceous sponges; tests of radiolaria are wanting, or are very rare. An analysis of red mud from the sea bottom off the Brazilian coast is given in table 32.[149] The average physical composition of a red mud is given in table 33.

TABLE 32

	PER CENT
SiO_2	31.66
Al_2O_3	9.21
Fe_2O_3	4.52
CaO	25.68
MgO	2.07
Na_2O	1.63
K_2O	1.33
SO_3	0.27
CO_2	17.13
Cl	2.46
Loss on ignition	6.02
	101.98

The sodium and chlorine shown in the chemical analysis may have been derived from the sea water retained in the mud. The iron content is not high, whereas the quantity of lime estimated to be present as the carbonate

[149] Murray, J., and Renard, A. F., Deep sea deposits, analysis by Hornung, M., pp. 444–445.

is nearly 40 per cent, the material shown in the analysis being of the nature of a marl. All red muds, however, do not have so great a lime content.

Although these muds are red at the surface, there is nothing to indicate the persistence of that color with depth, and the quantity of organic matter suggests reduction of the ferric oxide soon after burial.

Red muds are estimated to cover about 100,000 square miles of the ocean bottom, and the "Challenger" samples were collected at depths ranging from 500 to over 1000 fathoms.[150] The three regions of greatest extent are along the Brazilian coast near the mouth of the Amazon, along the coast of Colombia near the mouth of the Orinoco, and in the Yellow Sea near the mouth of the Yangtze-Kiang.

TABLE 33

	PER CENT
$CaCO_3$:	
Pelagic foraminifera	13.44
Benthonic foraminifera	3.33
Other organisms	15.51
Residue:	
Siliceous organisms	1.00
Minerals	21.11
Fine washings*	45.61
	100.00

* The percentage of fine washings increases with depth, ranging from 33.37 per cent on bottoms shallower than 500 fathoms to 49.24 per cent on bottoms deeper than 1000 fathoms.

Red Clays

The red clays are confined to the deep abyss of the ocean, and are formed from the insoluble substances which have settled downward from the surface, together with such organic matter as is produced on, or attains, the bottom. The quantity of clayey matter and the shade of color vary somewhat, but Murray and Renard[151] state that the hydrated silicate of alumina is always present, and red is the prevailing color. In the North Atlantic the color is brick-red, but in the South Pacific a dark chocolate color prevails, due to the presence of very minute particles of manganese peroxide. The surface layers appear to be of a lighter color than those deeper, except in the North Pacific, where they are darker. The material is plastic, soft,

[150] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, p. 235.
[151] Murray, J., and Renard, A. F., op. cit., pp. 190–203.

and has a greasy feel. In a small fragment the red clay appears to be homogeneous, but in large masses it probably presents a heterogeneous aspect, due to the presence of shark teeth, bones of whales, ice-borne and other rafted material, volcanic ash, pieces of pumice of various di-

TABLE 34

	1*	2	3
	per cent	*per cent*	*per cent*
SiO_2	43.25	62.10	54.48
Al_2O_3	13.15	16.06	15.94
Cr_2O_3			0.012
Fe_2O_3	11.80	11.83	8.66
FeO			0.84
MnO_2		0.55	1.21
CaO	0.89	0.28	1.96
MgO	0.60	0.50	3.31
NiO, CoO			0.039
SrO			0.056
BaO			0.20
$CaSO_4$	2.24	0.37	
$CaCO_3$	16.42	0.92	
$MgCO_3$	2.70	2.70	
$Ca_3P_2O_8$	Trace	0.19	
K_2O			2.85
Na_2O			2.05
V_2O_3			0.035
As_2O_3			0.001
MoO_3			Trace
P_2O_5			0.30
CuO			0.024
PbO			0.008
ZnO			0.005
TiO_2			0.98
Loss in ignition	8.95	4.50	7.04
	100.00	100.00	100.00

* 1 and 2. Analyses by J. S. Brazier, Deep Sea Deposits, Challenger Rept., 1891, p. 198. Depth of 2700 fathoms for 1 and 3125 fathoms for 2.

3. Analyzed by G. Steiger, composite of 51 samples, in Clarke, F. W., Bull. 770, U. S. Geol. Surv., 1924, p. 518.

mensions, particles of cosmic origin, nodules of manganese and phosphorus, fragments of foraminifera, minerals commonly occurring in igneous rocks, and minerals arising from diagenesis, such as various zeolites, of which one resembling phillipsite is common in the red clays of the South Pacific and

Indian oceans. Carbonate of lime ranges from nothing to 28.88 per cent, the average of 70 samples collected by the "Challenger" being 6.70 per cent. The percentage of lime decreases with depth of water. Determinable mineral particles in the red clays usually are very small, ranging from 0.1 to 0.85 mm. in diameter, and compose only a small per cent of the whole, the average in the "Challenger" samples being 5.56 per cent. These particles are usually angular and have an average diameter ("Challenger" samples) of 0.08 mm. The remaining constituent of red clay is mostly the hydrated silicate of aluminum, and much of this is of colloidal dimension. Analyses of red clay are given in table 34. It is obvious that there is much variation in chemical composition.

TABLE 35

	PER CENT
$CaCO_3$:	
Pelagic foraminifera	4.77
Benthonic foraminifera	0.59
Other organisms	1.34
Residue:	
Siliceous organisms	2.39
Minerals	5.56
Fine washings	85.35
	100.00

The high content of fine washings emphasizes the finely divided character of the red clay constituents.

The average physical composition[152] of red clay is given in table 35.

Red clays cover the bottom of the ocean over an area of 51,500,000 square miles, of which 5,800,000 square miles are in the Atlantic, 4,900,000 square miles in the Indian, and 40,800,000 square miles in the Pacific. The mean depth of its occurrence is 2730 fathoms, but it is found in depths as shallow as 2000 fathoms.

Blue and Gray Muds

Blue and gray muds are found on the deeper marine bottoms adjacent to the land and on the deeper bottoms of all enclosed or partially enclosed bodies of water. The depth may be very shallow, but conditions must not be favorable for deposition of gravel, sand, carbonates, or much organic matter. Composing materials are varied and are the products of decomposition and

[152] Murray, J., and Renard, A. F., op. cit., 1891, p. 197.

disintegration, together with more or less matter of organic origin. If organic matter is of large quantity, black muds and silts may be deposited. At the surface the colors may range to reddish or brownish, but beneath the surface they range from gray to blue. The color beneath the surface is due to organic matter and finely divided ferrous sulphide. As the surface layer becomes covered by succeeding deposits, the iron oxide or hydroxide to which surface colors are due becomes changed to ferrous sulphide, ultimately resulting in marcasite or pyrite. Hydrogen sulphide is rather constantly present in the blue and gray muds. There may be some coarse material, and fragments of shells are not uncommon.

Determinable mineral particles present in blue and gray muds are those characteristic of the adjacent lands, and there is hence as great variation

TABLE 36

	1*	2
SiO_2	63.36	64.20
Al_2O_3	15.08	13.55
Fe_2O_3	11.23	8.38
$CaCO_3$	1.75	2.94
CaO	1.63	2.51
$CaSO_4$	0.58	0.42
$Ca_3P_2O_8$	Trace	1.39
$MgCO_3$	1.14	0.76
MgO	0.31	0.25
Loss on ignition	4.92	5.60
	100.00	100.00

* No. 1 is from the Pacific and No. 2 from the Atlantic. The close similarity in the analyses is noteworthy.

as localities permit. Dimensions of particles decrease with distance from the land and depth of water. Quartz usually is most abundant, and in many cases more than half is made up of quartz fragments. The particles are usually angular, and the dimensions in the "Challenger" samples range from 0.006 to 0.30 mm., the average being 0.115 mm. The percentage of these larger particles ranges from 1 to 75 per cent, with an average of 22.48 per cent. Glauconite is present in limited quantity. The fine washings, or material too small for easy determination, averages 61.77 per cent.

The carbonate of lime in the blue muds collected by the "Challenger" expedition varies from a trace in the greater depths to 34.34 per cent in 500 fathoms, and the average is 12.48 per cent. There is no marked increase in the lime content with depth, as is the case with purely pelagic deposits,

but the smallest lime content is found in the greatest depths. This lime is derived from calcareous organisms which belong to both the benthos and plankton. Some siliceous organic matter is also commonly present, this in the "Challenger" samples ranging from 1 to 15 per cent. Analyses of blue muds are given in table 36.[153]

The physical composition of blue and gray muds is given in table 37. As in other marine muds, the percentage of fine washings increases and the lime content decreases with depth.

Blue and gray muds are thought to cover about 14,500,000 square miles of the ocean bottom, of which 4,000,000 are in the Arctic, 3,000,000 in the Pacific, 2,000,000 in the Atlantic, 1,500,000 in the Indian, 1,500,000 in the Southern, and 2,500,000 in the Antarctic. The "Challenger" found the

TABLE 37

	PER CENT
$CaCO_3$:	
Pelagic foraminifera	7.52
Benthonic foraminifera	1.75
Other organisms	3.21
Residue:	
Siliceous organisms	3.27
Mineral particles	22.48
Fine washings	61.77
	100.00

* Murray, J., and Irvine, R., Trans. Roy. Soc. Edinburgh, vol. 37, 1895, p. 482; Murray, J., and Renard, A. F., op. cit., 1891, p. 232.

depths to range from about 225 to 5,120 meters, with the average 2,580 meters. The "Valdivia" found blue mud from 219 to 5,214 meters, the average being 1,934 meters.

Green Muds

Green muds derive their color from the presence of finely divided glauconite, and to some extent from glauconite of sand-grain magnitude. There is also mixed with the muds a greenish amorphous substance which appears to be of organic origin. Some of the green may also be due to chlorite and perhaps other substances, and this is apt to be the case after the muds have changed to shales.

Green muds differ from green sands chiefly in the association of quartz

[153] Murray, J., and Renard, A. F., Deep sea deposits, 1891, p. 232.

sand with the latter. The chief distinction from blue and gray muds is the presence of glauconite. This appears to form as a consequence of certain relations between the quantity of organic matter in the sediments and the other materials. If there is an excess of organic matter, blue to black mud appears to result, in which hydrogen sulphide develops, with the ultimate formation of ferrous sulphide. If the organic matter falls below a certain, not yet determined, percentage, ferrous sulphide does not form, but reactions occur that result in the potassium silicate of iron or glauconite.[154] If muds contain a large quantity of ferric oxide or hydroxide, or are accumulated rapidly, glauconite does not develop, and hence these muds are not green.

The compositions of green muds are similar to those of the gray and blue muds. Determinable mineral particles range from 1 to 80 per cent and

TABLE 38

	PER CENT
SiO_2	31.27
Al_2O_3	4.08
Fe_2O_3	12.72
CaO	0.30
MgO	0.12
$CaCO_3$	46.36
$Ca_3P_2O_8$	0.70
$CaSO_4$	0.58
$MgCO_3$	0.57
H_2O loss on ignition	3.30
	100.00

average about 27 per cent. Many are composed of glauconite, and these approximate spherical shapes. The other particles are mostly angular and range in diameter from 0.06 to 0.20 mm. They consist of quartz, feldspar, magnetite, hornblende, augite, and occasional particles of tourmaline, zircon, and garnet. Small to large nodules of calcium phosphate are also present. The dimensions and abundance of recognizable mineral particles decrease with depth. Under 500 fathoms the identifiable mineral particles average 29 per cent of the samples, with average diameter of 0.145 mm.; in depths exceeding 1000 fathoms the quantity of determinable mineral particles averages 17.50 per cent, and the average diameter has decreased to 0.1 mm. Calcium carbonate is almost always present, ranging from very small amounts

[154] Collet, L. W., Les dépôts marins, 1908, pp. 51–52.

to over 50 per cent. Analyses of green muds are given in table 38, and the average physical composition in table 39.[155]

Green muds were found by the "Challenger" expedition to cover parts of the ocean bottom from depths of 100 to 1270 fathoms, with the mean depth 513 fathoms. With the green sands they form a discontinuous band on the edge of the continental shelf, the area covered by them being estimated to be about 1,000,000 square miles. They are extensively distributed along the coasts of Portugal and Spain in depths less than 1830 meters. The "Blake" expedition found green sands and green muds from Cape Hatteras to 31°48′ N. in depths of 91 to 183 meters. Depth seems to be a factor in their development, but it is not the controlling one.

TABLE 39

	PER CENT
$CaCO_3$:	
Pelagic foraminifera	14.59
Benthonic foraminifera	2.94
Other organisms	7.99
Residue:	
Siliceous organisms	13.67
Mineral particles	27.11
Fine washings	33.70
	100.00

Black Muds

The black or carbonaceous and bituminous shales which are extensively developed in parts of the American sequence, and more or less equally so in sequences of other parts of the world, originated in black or dark blue muds rich in organic matter. In some occurrences they are in the form of occasional thin beds interstratified with other sediments; in others they compose entire formations. There appear to be two kinds: one in which the coloring is due to coaly material, and the other in which it is due to a substance from which petroleum may be distilled. The former may be termed carbonaceous, the latter bituminous. They develop both in fresh and salt water.

Black shales usually are soft, and a resemblance to slate has led to their being in many instances so identified. Ordinarily they are well bedded, and in many occurrences the laminations are of paper thinness. Thin

[155] Brazier, J. S., Deep sea deposits, Challenger Repts., 1891, p. 449.

layers of conglomerate are not uncommonly present, and thin beds of more or less cross-laminated sandstone are also common. An analysis[156] of black shales is given in table 40.

The high percentage of sulphur in black shales is noteworthy and indicates strongly reducing conditions during accumulation.

Black shales may be almost barren of macroscopic fossils, but a common occurrence is the occasional presence of thin layers literally crowded with delicate forms. Ordovician and Silurian bituminous shales almost invariably contain graptolites; the Devonian and Mississippian bituminous shales, spores and spore cases, resin lumps, and conodonts; and black shales

TABLE 40

	PER CENT
C	13.11
SiO_2	51.03
Al_2O_3	13.47
Fe_2O_3	8.06
CaO	0.78
MgO	1.15
Na_2O	0.41
K_2O	3.16
H_2O	0.81
P_2O_5	0.31
S	7.29
Hydrocarbons	3.32
	102.90
Less O	2.73
	100.17

of the later geologic systems, the same materials as in the Mississippian and the Devonian with possibly the conodonts lacking. Remains of algæ are said to be common.[157] Carbonaceous black shales contain remains of higher plants. The faunas of the bituminous black shales are singularly uniform for any given stratigraphic unit, and mature shells of benthonic species are not common. Brachiopod shells are those of young individuals, those of species whose mature individuals are small, or those possessing phosphatic

[156] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 552. Analysis by L. G. Eakin. Bituminous shale from Dry Gap, Georgia.

[157] The reader should consult, David White, this book, topic Oil Shales, and Conacher, H. R. J., A study of oil shales and torbanites, Trans. Geol. Soc. Glasgow, vol. 16, 1916, pp. 164–192.

and chitinous tests; the last group usually include the largest brachiopod shells present, and many of these belong to genera with long geologic ranges. They are mostly inarticulates of linguloid or oboloid types. The pelecypod shells either belong to mud burrowers, or are those of young individuals or small forms. Many black shales contain shells of cephalopods. Trilobites occur in some Paleozoic bituminous shales, wherein they commonly have the aspect of either burrowers or plankton. If the mud-burrowing forms be disregarded, the faunas of the bituminous black shales have the appearance of having belonged to the plankton, and the occurrence of the young of species which in other environments reach normal size suggests that these floated into the waters where the black muds were depositing. The mud-loving forms, on the other hand, probably lived where the shells are found. Many species have wide distribution.

The fossils of black shales are generally composed of iron sulphide or are carbonized. Carbonized fossils are usually those which in the living condition had shells composed of chitin or a similar substance. Shells which originally were composed of calcium carbonate are commonly changed to pyrite or marcasite. Thus, the tests of graptolites, crustacea, and some brachiopods usually consist of carbonaceous matter; those of cephalopods, pelecypods, and other brachiopods are frequently pyritized. Nodules of pyrite and marcasite are also common in black shales.

A summary of the characteristics of black shales gives the following: the shales are thinly laminated, but this is not invariable; they may have extensive linear distribution; thinly laminated sandstones are distributed through them to a greater or less extent; there are occasional bands of conglomerate; the most abundant fossils belong to the plankton; some fossils have wide distribution; there is a sparseness of benthonic forms; carbonaceous and bituminous shales are not infrequently interstratified with coal beds; many black shale formations pass laterally into other types of deposits. Any explanation relating to the origin of carbonaceous and bituminous shales must harmonize with these characteristics.

Clarke[158] concluded that the Genesee black shales were deposited in waters of depths and characteristics similar to those of the Black Sea, some of whose sediments,[159] from 100 to 800 fathoms, consist of fine, sticky, dark muds in which there is much ferrous sulphide, abundant remains of planktonic diatoms, and fragments of young pelecypods; and at greater depths light blue muds which do not contain so much ferrous sulphide, but considerable minutely grained calcium carbonate which in some cases makes thin

[158] Clarke, J. M., Mem. 6, New York State Mus. 1903, pp. 199–201.

[159] Andrussow, N., La Mer Noire, Guide to the excursions of the Seventh Internat. Geol. Congress, 1897, p. 27; see also, Geog. Jour., vol. 1, 1893, pp. 49–51.

bands. These muds are postulated by Clarke to yield a shale like that of the Genesee.

Pompeckj has interpreted the black Jurassic shales of Bavaria and the Permian Kupferschiefer of western and north Germany as having developed in a similar environment.[160]

The above hypothesis accords fairly well with some of the facts requiring explanation, and it may be that some of the black shales developed in an environment similar to that represented by the bottom deposits of the Black Sea. It does not, however, explain those shales with which are interstratified cross-laminated sandstones and beds of conglomerates. Neither does it explain the interstratification with beds of coal, nor the linear distribution which some of the black shale formations exhibit.

Schuchert states that black shales of wide distribution probably originated "in closed arms of the sea (cul de sacs), or when of small areal extent, as the result of fillings of holes in the sea bottom," the "halistas" of Walther and the "dead grounds" of Johnstone, and are the result of poor circulation and consequent deficiency of oxygen. He also suggests that black muds may develop from the deposits of Sargasso seas, but as the deposits of these "seas" are little known, and the supposed accumulations appear to have little basis in fact, the suggestion can be given little weight.[161]

Ruedemann considers that the most essential requisite for the formation of the black carbonaceous graptolitic shales is not depth but tranquillity of water, and he considers that they

> indicate a zone between the agitated water, where coarser sediments are deposited, and the dead or currentless water of deep sea. Their longitudinal distribution, then, also indicates the direction of a coast line, which has to be sought on the farther side of a parallel band of coarser littoral sediments, and two such flanking littoral bands may be looked for in narrow channels like the Levis Channel.[162]

There is little support for this hypothesis.

Ulrich is of the opinion that

> the graptoliferous black shales of the Levis, Athens, and Ouachita troughs, in which there are thicker beds of such shale than anywhere else in America, prove as certainly as anything that inclosed and stagnant conditions are not essential to black shale deposition. That

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[160] Pompeckj, J. F., Die Jura-Ablagerungen zw. Regensburg und Regenstauf, Geogn. Jahresh., München, 14. Jahrg., 1901, pp. 178–186. Das Meer des Kupferschiefers, Branca-Festschrift, 1914, pp. 444–494, summarized by Schuchert, Chas., Proc. Am. Philos. Soc. vol. 54, 1915, pp. 259–269.

[161] Schuchert, C., Biologic principles of paleogeography, Pop. Sci. Mon., 1910, pp. 598–599.

[162] Ruedemann, R., Stratigraphic significance of the wide distribution of graptolites Bull. Geol. Soc. Am., vol. 22, 1911, p. 234.

most graptolites were pelagic in habit and passed from one ocean basin into another solely by means of marine currents is universally accepted. They could not have entered a continental basin except a marine current carried them in, and there is no normal possibility of their transportation to the head of a narrow bay. Consequently, when it is established that the deposits in question are confined to narrow strips hundreds of miles in length, it is at the same time proved that they were laid down in channels open at both ends so as to give free passage and egress to the graptolite bearing currents. Marine thoroughfares like these surely cannot be called inclosed, nor does it seem possible that they could have become stagnant. And the not infrequent occurrence of intraformational conglomerates in these graptolite shales is almost conclusive proof that the channels were not of unusual depth.[163]

The above conclusions are based on the hypothesis that the black shales considered were deposited in channels connecting larger bodies. It does not seem probable that many black shales originated in channels as thus postulated unless conditions were such as to prevent circulation, and the suggestion that "stagnant conditions are not essential to black shale deposition" can hardly be given serious consideration. Furthermore, the channel idea to account for the linear distribution of the Lower Paleozoic black shales had best pass into the discard.

Ulrich further suggested that climatic conditions might have been responsible in that the waters were so cool as "to render their shores inhospitable to contemporaneous littoral and benthonic life," and he thinks this suggestion is favored by the evidence bearing on climate during several of the times when black shales were extensively deposited. He does not consider that any "of the black shale deposits in America is comparable in the matter of depth and inclosure of waters in which they were laid down to black muds in the Black Sea today," a view also expressed by Schuchert.

On the east shores of the Baltic, black muds are accumulating, which, if preserved, will ultimately result in black bituminous shales. These develop in bays of the mainland and islands and in sounds between the islands and the mainland. The organic matter is derived from both plants and animals, apparently chiefly the former. As the tides are weak, there is little circulation, and the waters appear to be deficient in oxygen. There is certainly a great development of hydrogen sulphide, and the bottom is virtually uninhabited by visible animals. Occasional storms sweep planktonic forms into these bays, and their dead shells locally mantle the bottom, as was observed in splendid occurrence in the sound between the islands of Moon and Oesel. Occasional layers of pebbles are also brought in. Obviously here is a place where deposits of black shales with characteristics similar to those of the geologic column are now forming. The deposits, however, are of

[163] Ulrich, E. O., Revision of the Paleozoic systems, Bull. Geol. Soc. Am., vol. 22, 1911, p. 358.

small extent and would appear in a future geologic section as patches, and in no way are they comparable to the immense extent of the Kupferschiefer, the Utica, Cherokee, and other black shale formations.[164]

As a result of their studies of the black graptolite shales of southern Sweden and the Moffatdale region of southern Scotland, Grabau and O'Connell[165] came to the conclusion that these shales could not have been deposited in deep waters. The black shales of southern Sweden must have been deposited along shore, as they rest on an eroded surface. The southern Scotland black shales are interpreted as "mud deposits on the flood plain and in the lagoons of a large delta or series of deltas where periodic high tides washed in the planktonic graptolites and stranded them on the flats." Grabau also interprets the black muds of the Permian Kupferschiefer as lagoonal deposits.[166] In his latest consideration of the environment of formation of graptolite bearing shales, Grabau[167] analyzes the data given in two recent papers by advocates of the deep sea origin of these sediments[168] and points out that the advocates of deep sea deposition offer few or no data that are not possible of other interpretation. He refers the deposition of the graptolite shales to lagoons, mud flats, and low lying lands bordering the sea. The *normal* graptolite shales are said to be the most wide spread and to consist of thin layers of black mud intercalated between thicker beds of shales and shaly sandstones. These shales contain very few marine fossils and particularly few benthos. The graptolites are mainly in the thin black shales. The coarser sediments are interpreted by Grabau as the fluvial deposits over flood plains like those of the Hwang-Ho of China, the Indo-Gangetic plain of India, the Euphrates-Tigris of Mesopotamia, and the Amur of Siberia, and the graptolite layers are considered as marine deposits laid down during inundations of the sea over the flood plains. The *black shale* type, as defined by Grabau, is that which is generally black throughout, contains graptolites at frequent levels, and contains more marine organisms than are found in the normal type of graptolite shales. Typically marine

[164] Twenhofel, W. H., Notes on black shale in the making, Am. Jour. Sci., vol. 40, 1915, pp. 272–280. See also Goldman, M. I., "Black Shale" formation in and about Chesapeake Bay, Bull. Am. Assoc. Pet. Geol., vol. 8, 1924, pp. 195–201.

[165] Grabau, A. W., and O'Connell, M., Were the graptolite shales, as a rule, deep or shallow water deposits?, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 959–964.

[166] Grabau, A. W., Comprehensive geology, vol. 2, 1921. p. 513.

[167] Grabau, A. W., Origin, distribution, and mode of preservation of the graptolites, Nat. Res. Inst. China, Mem. Inst. Geol., no. 7, 1929, pp. 1–52.

[168] Marr, J. E., Conditions of deposition of the Stockdale shales of the Lake District, Quart. Jour. Geol. Soc., vol. 81, 1925, pp. 113–136; Ruedemann, R., Faunal facies differences of the Utica and Lorraine shales, Bull. 267, New York State Mus., 1926, pp. 61–77. The deep sea origin of the black graptolite shales seems to have been first suggested by Professor Charles Lapworth.

benthonic forms, however, are wanting or rare. These shales are interpreted as deposits made by well graded rivers in estuaries along the borders of alluvial plains or over mud flats bordering such plains.

The present writer is in complete agreement with Grabau with respect to all the black graptolite shales with which he has familiarity that these can not be considered the deposits of deep water. They are all interpreted as deposits made in shallow water adjacent to the shore. He is not able to follow Doctor Grabau in considering any part of the black graptolite shales which he has seen as having resulted from deposition over flood plains.

Scupin[169] seems independently to have arrived at the view that graptolite shales result from the periodic flooding of low lands by marine waters and he defines the shales studied by him as true sapropelites (Faulschlammablagerung) dammed up behind dunes of Obolus sandstone.

The black bituminous and carbonaceous shales have several characters which must be given full weight when seeking for the environment of origin. The carbonaceous shales contain no or rare marine organisms, and they are low in iron sulphides. The environment was not marine; the associated waters were low in sulphates; and the deposits accumulated under conditions eliminating, or restricting the activities of, the aërobic bacteria. The bituminous black shales frequently contain marine fossils; these in many instances are of extremely delicate and perishable character; and the containing beds often have them in considerable abundance. There is a scarcity of benthonic forms. The high content of organic matter proves reducing conditions; the sulphides show the work of sulphide bacteria and the probable abundance of hydrogen sulphide in the muds and associated waters; the absence of benthos proves bottoms unfit for their occupation; and the preservation of delicate and perishable organic matter, as the graptolites of the Utica shales and the annelids and other organisms of the Cambrian Burgess shale, proves the absence of bottom scavengers. A basin or some part of a basin with extremely poor circulation of those waters in contact with the bottom must be postulated. Depth and temperature are not essential factors; poor circulation of water is; and the initial deposits will form in any depth permitting accumulation of organic matter in quantities greater than can be decomposed. Low temperature may aid, as such discourages decomposition, and depth may assist in lowering temperature.

It seems certain that the conditions essential for black shale formation may occur in several different environments. Such sediments are now being deposited over parts of the bottom of the Black Sea, in deep holes on the sea bottom, in the bays of seas with weak tides, in swamps, and some

[169] Scupin, H., Ist der Dictyonemaschiefer eine Tiefseeablagerung?, Zeits. d. D. Geol. Gesells., vol. 73, Monatsb., 1921, pp. 153–155.

lakes. Except for deep holes in the bottom of the neritic and bathyal marine environment, it is not considered probable that black shales have much development in the open sea.

CLAYS AND SILTS OF VOLCANIC ORIGIN

Over parts of the land and on the bottoms of bodies of water adjacent to volcanic islands and coasts are sediments composed of the fine products of volcanic activity. The best development is about the oceanic volcanic islands. Near shore the deposits contain many particles of sand dimension; in the deeper waters these drop out, and fine particles dominate. Volcanic sediments are mingled to greater or less extent with sediments of other origin, but also occur essentially pure. They may occur in any depth of water and on any height of land, but in the shallow waters so much other material is apt to be incorporated and so much alteration is likely to occur that characteristic features are not present.

Volcanic muds present great variety in character depending on whether deposited on land or in water, and if the latter, on the depth of water and the organic and other incorporated remains. The colors of ash deposited on the land are white to gray as a rule, whereas in the sea the range of colors is from light gray through brown to black.

The main constituent of volcanic muds is glass, of which the particles are angular and have surfaces which are sections of bubble boundaries. Other constituents are crystalline particles of minerals which result from rapid cooling of lava. These are feldspar, quartz, zircon, hornblende, mica, etc. Deposits of ash made on land are not apt to contain much else than the above; those made in the sea contain some lime in the form of shell matter, which in the "Challenger" samples was found to range from a trace to over 56 per cent. The average physical compositions of marine volcanic mud and volcanic sand are given in table 41.

Ash deposits made on the land decrease in thickness outward from the crater of origin, and as they are distributed by winds, greatest distribution leeward of the source is likely. Stratification is poor or wanting, and the deposit is parallel to the topography. Ash deposits made in water are well stratified, and in the sea the beds have wide distribution and continuity and pass gradually into other types of marine deposits.

Volcanic ash deposits are rather common in the Tertiary of western North America, having been described from Kansas,[170] Nebraska,[171] Oklahoma,[172]

[170] Landes, K. L., Volcanic ash in Kansas, Bull. Geol. Soc. Am., vol. 31, 1928, pp. 931–940. Two horizons, one in Tertiary, one in Pleistocene. Ash did some drifting, as cross-lamination is present.

[171] Barbour, E. H., Nebraska pumicite, Nebraska Geol. Surv., vol. 4, 1916, pp. 357–401, pl. 27.

[172] Buttram, F., Volcanic dust in Oklahoma, Bull. 13, Oklahoma Geol. Surv., 1914.

Montana, Wyoming, and elsewhere, and one of the recent geologic past from Alaska.[173] The Kansas and Nebraska beds are well known for their extensive distribution and purity. Another famous deposit is that of Florissant, Colorado, noted for its fossil leaves and insects. A deposit of immense magnitude is that made in the Valley of Ten Thousand Smokes in Alaska and connected with the 1912 eruption of Katmai volcano. This deposit consists mainly of pumice and ash, and an estimated total of one hundred and fifty billion cubic feet was ejected. The maximum thickness is 200 feet. The material appears to have been hot when deposited and hence not truly sedimentary.[174]

Marine deposits of volcanic ash have been thought to be rather uncommon in the older rocks of the geologic column, but the advance of exploration has indicated that such may be more extensive than generally supposed.

TABLE 41

	VOLCANIC MUD	VOLCANIC SAND
	per cent	*per cent*
$CaCO_3$:		
Pelagic foraminifera	10.50	13.00
Benthonic foraminifera	2.82	3.80
Other organisms	7.17	11.99
Residue:		
Siliceous organisms	1.82	1.40
Minerals. Includes glass	40.82	60.00
Fine washings	36.87	9.81
	100.00	100.00

The common occurrence of volcanic particles in modern marine deposits suggests an equal commonness in the sediments of the older systems. Studies of the Cretaceous Mowry shale of the Black Hills led Rubey[175] to the conclusion that the high silica content of this shale is due to the "chemical decomposition of slowly accumulated, very fine grained, highly siliceous volcanic ash in the presence of decaying organic matter," and work done by Ross, Miser, and Stephenson has shown the occurrence of volcanic materials in every formation of the Upper Cretaceous of Texas and in parts

[173] Capps, S. R., jr., An ancient volcanic eruption in the Upper Yukon Basin, Prof. Paper 95, U. S. Geol. Surv., 1915, pp. 59–64.

[174] Fenner, C. N., Nat. Geog. Soc., Contributed Technical Papers, Katmai Ser., no. 1, 1923, pp. 63–67.

[175] Rubey, W. W., Origin of the siliceous Mowry shale of the Black Hills region, Prof. Paper 154, U. S. Geol. Surv., 1929, pp. 153–170.

of that system in Arkansas and Oklahoma.[176] In the Cretaceous of western North America, and to a less extent in other systems, occur sedimentary rocks known as bentonite. Pure and unweathered bentonite has a white to cream color, but on weathering it becomes yellow to brown or red; green and blue colors are not uncommon. It is noted for its ability to adsorb as much as eight times its volume of water and to swell in greater proportion, a characteristic which seems to be dependent on the finely divided nature of the composing material and its composition. On adsorbing the water it first becomes sticky and plastic; with excess of water a soapy slime is formed. Organic matter is rare in bentonite beds, and fossils have rarely been reported therefrom. It usually is well stratified.

Bentonite from the Big Horn basin of Wyoming is composed of two kinds of material.[177] The particles of sand and silt dimensions consist mostly of plagioclase (andesine), orthoclase, and biotite. Accessory substances are quartz, glass, apatite, zircon, and agate. The feldspars are angular and uniformly fresh and unaltered, and the apatite and zircon have crystal terminations. Most of the grains of quartz are angular; a few are well rounded. The other part of bentonite consists of alumina, silica, water, and various minor chemical constituents, 73 to 86 per cent being of this composition. There are many bentonites in which it is obvious that impurities were introduced. A deposit around the southern edge of the Black Hills, studied by Wherry,[178] shows no quartz, but the other minerals are present, and, in addition, there is some magnetite. The larger particles are adjacent to bases of beds. The silica-alumina ratio in this bentonite is between 3 and 4 to 1. Bentonite (meta-bentonite) from Tennessee is composed of a potash-containing clay mineral (originally identified as montmorillonite) and minor quantities of feldspar, quartz, zircon, and more or less colorless mica.[179] Bentonite beds with thicknesses from 1 to 7 inches which are probably extensions of those of Tennessee occur in central Pennsylvania for over 100 miles in a northeast-southwest direction. Four of the beds are near the base of the Trenton and one is in the Black River. The bentonite from the Black River is chiefly composed of montmorillonite with fine frag-

[176] Ross, C. S., Miser, H. D., and Stephenson, L. W., Water-laid volcanic rocks of early Upper Cretaceous age in southwestern Arkansas, southeastern Oklahoma, and northeastern Texas, Prof. Paper 154, U. S. Geol. Surv., 1929.

[177] Hewett, D. F., The origin of bentonite and the geologic range of related materials in Big Horn Basin, Wyoming, Jour. Washington Acad. Sci., vol. 7, 1917, pp. 196–198.

[178] Wherry, E. T., Clay derived from volcanic dust in the Pierre of South Dakota, Jour. Washington Acad. Sci., vol. 7, 1917, pp. 576–583.

[179] Larsen, E. S., in Nelson, W. A., Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama, Bull. Geol. Soc. Am., vol. 33, 1922, p. 613.

ments of biotite and a few grains of apatite, quartz, and feldspar. Volcanic glass and bogen structure are characteristic.[180]

Ross and Shannon[181] define bentonite as

a rock composed essentially of a clay-like mineral formed by devitrification and the accompanying alteration of a glassy igneous material, usually a tuff or volcanic ash; and it often contains variable proportions of accessory crystal grains that were originally phenocrysts in the volcanic glass. These are feldspar (commonly orthoclase and oligoclase), biotite, quartz, pyroxene, zircon and various other minerals typical of volcanic rocks. The characteristic clay-like mineral has a micaceous habit and facile cleavage, high birefringence, and usually a texture inherited from volcanic tuff or ash, and it is usually the mineral montmorillonite, but less often beidelite.

TABLE 42

	1*	2	3
	per cent	*per cent*	*per cent*
SiO_2	51.10	55.64	50.33
Al_2O_3	15.40	16.80	16.42
Fe_2O_3	4.50	2.68	2.42
CaO	5.20	1.80	1.39
MgO	3.80	8.88	4.10
K_2O	1.50	5.16	1.00
Na_2O		0.04	0.12
H_2O	17.10	9.72	23.95
	98.60	100.72	99.73

* 1. Bentonite, selected crude, Ardmore, South Dakota, analysis by E. T. Wherry op. cit., 1917, p. 580.

2. Bentonite, High Bridge, Ky., collected by C. Butts, purified by C. S. Ross, analyzed by E. V. Shannon.

3. Bentonite, Kern Co., California, selected crude. E. V. Shannon, analyst.

These analyses are taken from Ross and Shannon, 1926. The totals of 2 and 3 are different from the figures given by them.

Montmorillonite has the composition of "$(MgCa)O \cdot Al_2O_3 \cdot 5SiO_2 + nH_2O$,"[181] the ratio of alumina to silica being 1:5. One bentonite "that possesses this typical manner of origin is composed of a related clay-like mineral with a 1–3 alumina-silica ratio," which has been identified[182] as

[180] Bonine, C. A., Rept. Comm. Sedimentation, Nat. Research Council, 1924, p. 64.

[181] Ross, C. S., and Shannon, E. V., The minerals of bentonite and related clays and their physical properties, Jour. Am. Ceramic Soc., vol. 9, 1926, pp. 77–96 (79). See also Larsen, E. S., and Wherry, E. T., Jour. Washington Acad. Sci., vol. 15, 1925, p. 465.

[182] Larsen, E. S., and Wherry, E. T., Leverrierite from Colorado, Proc. Washington Acad. Sci., vol. 7, 1917, pp. 208–216.

leverrierite, and is now known as beidellite.[183] Montmorillonite also develops in the decay of other rocks besides volcanic tuffs, as for instance, that in association with the altered pegmatite near Branchville, Connecticut,[184] but the work done to date[185] "seems to indicate that other modes of origin normally result in a mineral with a lower alumina-silica ratio and especially the 1:3 ratio."

Table 42 gives analyses of four bentonites. They have been recalculated on the basis of no water. In table 43 are given analyses of montmorillonite and beidellite.

The bentonite from Kentucky is from strata of the Ordovician system; the two others are from Mesozoic or later strata. The high potash and low

TABLE 43

	1*	2	3
	per cent	*per cent*	*per cent*
SiO_2	48.60	50.60	47.28
Al_2O_3	20.03	17.23	20.27
Fe_2O_3	1.25		8.68
CaO	1.72	3.21	2.75
MgO	5.24	4.56	0.70
MnO	0.16		
$(K, Na)_2O$			0.97 Na_2O Trace K_2O
H_2O	21.52	24.32	19.72
	98.52	99.92	100.37

* 1. Montmorillonite from Montmorillon, France, analyzed by E. V. Shannon.

2. Theoretical composition of montmorillonite to satisfy formula $(Mg\cdot Ca)O\cdot Al_2O_3\cdot 5SiO_2\cdot 8H_2O$ with $MgO:CaO::2:1$.

3. Beidellite ("leverrierite") gouge clay from Beidel, Col., Larsen, E. S., and Wherry, E. T., op. cit., pp. 208–217.

water content of the Kentucky bentonite is noteworthy, but the water of the bentonite minerals seems in large part adsorbed, and it is assumed that such is the case for the potash,[186] although the potash could not be extracted with hydrochloric acid, and it may be in chemical combination.[187]

The mineralogical compositions of the Ordovician bentonites of the Appalachian region are shown in table 44.[188]

[183] Ross. C. S., and Shannon, E. V., The chemical composition and optical properties of beidellite. Jour. Washington Acad. Sci., vol. 15, 1925, p. 467.

[184] Ross and Shannon, op. cit., pp. 86, 90.

[185] Ross, C. S., and Shannon, E. V., Personal communication, Jan. 17, 1924.

[186] Ross, C. S., and Shannon, E. V., op. cit., pp. 91–93.

[187] Kerr, P. F., in Ross, C. S., Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, p. 148.

[188] Ross, C. S., Altered Paleozoic volcanic materials and their recognition, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 143–164.

Some bentonite beds are remarkable in their uniform thickness and character over extensive areas, and in the Big Horn Basin and other parts of Montana and Wyoming and about the Black Hills there are beds which can be followed for many miles with extremely slight variations in thickness and general appearance. This is true not only for beds of 3 to 4 feet thickness, but also for those which are but an inch or so thick. Bramlette[189] has found bentonite in the Cretaceous of Louisiana, and it occurs in the Cretaceous of Arkansas, Texas, and Oklahoma.[190] Nelson[191] has described bentonite in the Ordovician strata of Alabama, Kentucky, Ohio, Tennessee, and Virginia, where it occurs on five different horizons, and Bonine[192] has discovered what may be the same beds in Pennsylvania. Other students have extended the knowledge of the distribution of what may be these same beds into New York, Ontario, Minnesota, and Missouri.[193]

TABLE 44

	1*	2	3
	per cent	*per cent*	*per cent*
Bentonitic clay mineral	79	80	75
Orthoclase	16	13	12
Quartz	3	4	7
Biotite	2	3	5
Zircon		Trace	1
	100	100	100

* 1. High Bridge, Kentucky.
2. Birmingham, Alabama.
3. Catawba, Virginia.

Most bentonite is believed to develop through the alteration of volcanic ash, a view first advanced by Hewett. The facts on which the view is based are the uniform composition and thickness over a great area, the mineral

189 Bramlette, M. N., Bentonite in the Upper Cretaceous of Louisiana, Bull. Am. Assoc. Pet. Geol., vol. 8, 1924, pp. 342–344.

190 Ross, C. S., Miser, H. D., and Stephenson, L. W., op. cit., 1929, p. 185.

191 Nelson, W. A., Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama, Bull. Geol. Soc. Am., vol. 33, 1922, pp. 605–616.

192 Bonine, C. A., Rept. Comm. Sedimentation, Nat. Research Council, 1926, pp. 4–5. See also Ross, C. S., Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 149–150.

193 Kay, G. M., Stratigraphy of the Ordovician Hounsfield bentonite, Jour. Geol., vol. 39, 1931, pp. 361–376; Hounsfield metabentonite, Abstract, Bull. Geol. Soc. Am., vol. 42, 1931, p. 225; Allen, V. T., Altered tuffs in the Ordovician of Minnesota, Jour. Geol., vol. 37, 1929, pp. 239–248; Ordovician bentonite in Missouri, Abstract, Bull. Geol. Soc. Am., vol. 42, 1931, pp. 224–225; Maddox, D. C., Bentonite in the Ordovician near Collingwood, Ontario, Science, vol. 72, 1930, p. 630.

associations and volcanic matter which are present, and the difficulty of accounting for its origin by other sedimentary processes. The theory of origin given by Wherry[194] applies to the Cretaceous bentonites of the Northwest and is as follows: Ash settled in the Cretaceous sea, the heaviest particles sinking to the bottom first, thus becoming most abundant in the basal portion of each bed; as these particles were not exposed to atmospheric conditions, they underwent little change. The fine volcanic glass composing most of the ash is supposed to have been porous and to have contained various gases, so that a kind of autometamorphism took place,[195] with the clay-like mineral forming bentonite as the product. Wherry[196] suggests a mica-andesite ash for the bentonite south of the Black Hills, and Larsen states[197] that the Tennessee bentonite is a decomposed rhyolite ash which "altered immediately following eruption into a material somewhat akin to leverrierite." Ross and Kerr[198] state that "bentonites are most commonly derived from latitic glasses; that is, those high in feldspar, and containing little normative quartz." In every case deposition must have been very rapid; otherwise considerable proportions of sediment of other origin could not have failed to have become incorporated.

Criteria for the recognition of bentonites are the presence of glass relict structures and of minerals and crystals characteristic of volcanic rocks, the absence of non-volcanic minerals, the waxy luster, the reaction to water, and the optical and chemical properties.[199]

Another product of possible volcanic origin occurs in the Tertiary Green River formation of Utah and Colorado.[200] The materials are not clays, but they are discussed in this connection because of the possible similarity of their origin to that of bentonite. The materials are in "thin, more or less persistent beds resembling sandstone that consist almost wholly of perfect or euhedral crystals of the zeolite mineral, analcite," the crystals attaining maximum diameters of nearly 2 mm. Beds with relatively few zeolites have a "tufaceous matrix" consisting of silica in the form of chalcedony in

[194] Wherry, E. T., op. cit., 1917, pp. 582–583.

[195] Sargent, H. C., Paper given before Geol. Soc. London. Abstract in Nature, vol. 99, 1917, p. 59.

[196] Wherry, E. T., op. cit., 1917, p. 580.

[197] Larsen, E. S., in Nelson, W. A., op. cit., 1922, pp. 613–614.

[198] Ross, C. S., and Kerr, P. F., The clay minerals and their identity, Jour. Sed. Pet., vol. 1, 1931, p. 62.

[199] Ross, C. S., op. cit., 1928, p. 149. Other articles on bentonite are: Spence, H. S., Bentonite, Canada Bur. Mines, No. 626, 1924; and Connelly, J. P., and O'Harra, C. C., Bull. 16, South Dakota School of Mines, 1929, pp. 317–332.

[200] Bradley, W. H., Zeolite beds in the Green River formation, Science, vol. 67, 1928, pp. 73–74. The occurrence and origin of analcite and meerschaum beds in the Green River formation of Utah, Colorado, and Wyoming, Prof. Paper 158, U. S. Geol. Surv., 1929, pp. 1–7.

which are angular fragments of quartz, feldspar, biotite, and euhedral crystals of orthoclase, apatite, zircon, and more rarely plagioclase, hornblende, or pyroxene. An additional but rare zeolite is apophyllite. Analcite and apophyllite also occur in some of the shale beds, up to 10 per cent of the former and 2 per cent of the latter. The analcite beds contain no clay minerals or carbonates, although these are abundant in the associated shale beds in which there is also a little volcanic glass. The zeolites are postulated by Bradley to have resulted from interactions between various salts dissolved in lake waters and dissolution products of volcanic ash.

CLAYS AND SILTS OF EOLIAN ORIGIN

Eolian clays and silts have essentially universal distribution as minor constituents of almost, if not all, types of sediments. In certain instances they compose the major portions.

The loess is generally considered to be a wind deposit, but it has been interpreted as marine,[201] and very similar material develops from water deposition. Loess varies greatly in chemical composition, as is shown by the analyses given below, and it invariably contains an abundance of particles which result from rock abrasion, grinding, and impact. These particles are small and very little rounded. Those of the Chinese loess are in a "surprisingly fresh condition," and the average diameter of 758 measured grains was found to be 0.0124 mm.[202] Typical wind-deposited loess shows essentially no stratification, but the very similar material deposited in glacial lakes and the lakes of arid regions is likely to be well stratified. The mineralogical composition of loess is very diverse. That of Muscatine, Iowa, has quartz as the most important constituent,[203] other substances being orthoclase, plagioclase, hornblende, occasional fragments of biotite, tourmaline, some carbonates, and clay colored by iron oxide. Calcium carbonate is commonly, but not invariably, present.

A characteristic feature of loess deposits is the ability to maintain almost vertical cliffs. It has been suggested that this is due to the angularity of the composing particles, and to buttressing by rods and tubes referred to plant roots and stems over and about which the loess was laid down and in which calcium carbonate was later deposited. Unweathered loess has a light yellow color and is generally porous. The fossils of loess with few exceptions are of land origin and in large part consist of land snails. Many

[201] Kingsmill, T. W., The probable origin of deposits of "Loess" in North China and Eastern Asia, Quart. Jour. Geol. Soc., vol. 27, 1871, pp. 376–384.

[202] Barbour, G. B., The loess of China, Ann. Rept. Smithsonian Inst. for 1926, 1927, p. 283.

[203] Diller, J. S., The educational series of rock specimens, Bull. 150, U. S. Geol. Surv., 1898, p. 65.

loess deposits contain curiously shaped calcareous concretions, generally confined to definite horizons.

Analyses of loess and two adobe soils from the semi-arid regions of the West are given in table 45. Adobe is said to be very similar to loess in origin and physical composition, but the cited analyses show a lower silica content.

There has been much difference of opinion with respect to the origin of loess. It is not generally held to have been deposited by wind, this conclusion being based on the topographic position of much of it, the fact that the contained fossils are mostly of land origin and the remains of animals which live in water are wanting or very rare, and the general absence or rarity of any stratification. That the American and European loess has some connection with the Pleistocene glaciers or the conditions responsible therefor is suggested by the distribution with respect to the ice fronts, but

TABLE 45

	1*	2	3	4	5
	per cent	*per cent*	*per cent*	*per cent*	*per cent*
SiO_2	64.61	60.69	59.30	19.24	44.64
Al_2O_3	10.64	7.95	11.45	3.26	13.19
Fe_2O_3	2.61	2.61	2.32	1.09	5.12
FeO	0.51	0.67	1.55		
MnO	0.05	0.12		Trace	0.13
MgO	3.69	4.56	2.29	2.75	2.96
CaO	5.41	8.96	9.78	38.94	13.91
Na_2O	1.35	1.17	1.80	Trace	0.59
K_2O	2.06	1.08	2.17	Trace	1.71
H_2O	2.05	1.14	0.96	1.67	3.89
TiO_2	0.40	0.52	0.60		
P_2O_5	0.06	0.13	0.20	0.23	0.94
CO_2	6.31	9.63	7.41	29.57	8.55
C, organic	0.13	0.19		2.96	3.43
SO_3	0.11	0.12		0.53	0.64
Cl	0.07	0.08		0.11	0.14
	100.06	99.62	98.73	100.35	99.84

* 1. Loess from near Galena, Ill., Clarke, F. W., Bull. 770, U. S. Geol. Surv., 1924, p. 514.
2. Loess from Vicksburg, Miss., Clarke, F. W., op. cit., p. 514.
3. Loess from Kansu, China, Barbour, G. B., op. cit., 1928, p. 283.
4. Adobe from Salt Lake City, Utah, Clarke, F. W., op. cit., p. 514.
5. Adobe from Humboldt, Nevada, Clarke, F. W., op. cit., p. 514.

Leverett states:[204] "It has been determined that the greater part of the loess of the Mississippi basin was brought in from the semi-arid plains to the east of the Rocky Mountains, only a minor part being derived from the glacial deposits. The European loess deposits were also found to have been derived mainly from semi-arid districts." Richthofen expressed the opinion that the loess of China was produced in the arid regions of central Asia, blown to leeward by the prevailing winds, and deposited on the prairie lands where the grass cover prevented the further movement of most of it; some of it is conceived to have been redistributed by streams and lakes, thus accounting for the stratified portions.[205] Pumpelly[206] at first considered the Chinese loess a lake or terrace deposit; subsequently he adopted the view of Richthofen. According to Willis, the Chinese loess originated through the combined work of winds and streams, its origin being thought to be related to a change in climate from moist to arid. During the time of moist climate a deep residual soil developed, and when the climate changed to arid, this soil was removed to form the loess. The material was transported and sorted both by wind and water, generally moving downstream or eastward. Some was deposited on flood plains and in lake basins, and where thus deposited the material became stratified. Fine particles were carried by winds up the mountain slopes to settle in sheltered hollows and other places where the topography decreased the competency and capacity.[207] Barbour supports the view that the true loess of China is a wind deposit, the materials having been derived from dry regions to the west.[208]

The loess of Mississippi Valley has been referred to glacial production and deposition in Pleistocene icebound lakes and gorges,[209] partly to eolian, and partly to glacial and aqueo-glacial deposition,[210] and wholly to eolian deposition.[211] The Russian loess has been described as a glacial silt which was spread by both wind and water.[212]

The adobe of the arid basins of the West is a fine yellow clay and silt,

[204] Leverett, F., Problems of the glacialist, Science, vol. 71, 1930, p. 53.

[205] Richthofen, F. von, China, vol. 1, 1877, p. 74.

[206] Pumpelly, R., Relation of secular rock disintegration to loess, glacial drift, and rock basins, Am. Jour. Sci., vol. 17, 1879, pp. 133-144 (134-135).

[207] Willis, B., Research in China, Publ. 54, Carnegie Inst. Washington, vol. 1, 1907, pt. 1, pp. 184-185.

[208] Barbour, G. B., The loess of China, Ann. Rept. Smithsonian Inst. for 1926, 1927, pp. 279-296.

[209] McGee, W. J., The Pleistocene history of northeastern Iowa, Eleventh Ann. Rept., U. S. Geol. Surv., pt. i, 1891, p. 302.

[210] Chamberlin, T. C., Supplementary hypothesis respecting the origin of the loess of the Mississippi Valley, Jour. Geol., vol. 5, 1897, pp. 795-802.

[211] Keyes, C. R., Eolian origin of the loess, Am. Jour. Sci., vol. 6, 1898, p. 299.

[212] Hume, W. F., Notes on Russian geology, Geol. Mag., vol. 29, 1892, pp. 549-561.

which, according to Russell,[213] is of very much the same origin as the loess, except that the last agent of deposition was largely water. The fine deposits of glacial lakes resemble some loess, but the agents of deposition were water and the deposits are stratified.

That most loess is of eolian deposition appears probable. Most of the Mississippi Valley and European loess could hardly have been deposited by any agent other than wind, the original materials having been acquired from many sources but chiefly from bordering dry regions, the surfaces of ice sheets, and the out-wash fans and flood plains of melt-water streams. The Chinese loess is best referred to eolian deposition.

The greatest known development of loess in the geologic column is in the Pleistocene, in which it occurs in many parts of the world, chiefly in the northern hemisphere, where the total area covered by loess embraces many hundred thousand square miles. The greatest thickness probably occurs in China, but the previously reported thicknesses of 500 to 1500 feet seem doubtful. Andersson[214] placed the maximum thickness at 60 meters, later qualifying the figure by the addition of 20 or more meters. Barbour[215] states that cliffs of loess over 300 feet high have been measured by Dr. G. B. Cressey.

The Tertiary of western United States contains formations or parts of formations which have some aspects of loess. Matthew[216] has suggested that a part of the Oligocene White River clays may be fossil loess, the evidence supporting this suggestion being fineness of texture, absence of stratification, presence of land mammals, and comparative rarity of aquatic animals. Loomis has suggested a similar origin for the Miocene Harrison beds of Nebraska.[217] Lomas[218] states that some of the Keuper marls of western Europe have the appearance of loess, and he suggests that the materials were derived from the Triassic deserts which existed over parts of western Europe at that time. Paleozoic loess deposits have not been generally recognized. Grabau[219] states that the Devonian Nunda or Por-

[213] Russell, I. C., Subaerial deposits of the arid regions of North America, Geol. Mag., vol. 6, 1889, pp. 242–259, 289–295.

[214] Andersson, J. G., Essays on the Cenozoic of China, Mem. A, 3, Geol. Surv. China, 1923, p. 123.

[215] Barbour, G. B., op. cit., p. 281.

[216] Matthew, W. D., Is the White River Tertiary an eolian formation?, Am. Nat., vol. 33, 1899, pp. 403–409.

[217] Loomis, F. B., Turtles from the upper Harrison beds, Nebraska, Am. Jour. Sci., vol. 28, 1909, pp. 17–26.

[218] Lomas, J., Desert conditions and the origin of the British Trias, Geol. Mag., vol. 44, 1907, pp. 511–514, 554–563.

[219] Grabau, A. W., Principles of stratigraphy, 1913, p. 569. Comprehensive geology, vol. 2, 1921, p. 342. Miller, W. J., Origin of the color in the Vernon shales, Bull. 140, New York State Mus. Nat. Hist. (6th Rept. of Director for 1909), 1910, pp. 150–156.

tage shale of New York has the appearance of consolidated loess, and he made the same suggestion for the Silurian Vernon shale, but Newland[220] says that the latter is not loess.

It is very probable that with growth of knowledge loess will be found to be far more extensive in the geologic column than previously suspected. If there was no protecting land vegetation in the Pre-Cambrian and early Paleozoic, as ordinarily assumed, it would seem that loess should be common in the strata of those eras, as there would have been great opportunity for wind and rain wash to attack the surface, with the consequent production, transportation, and deposition of vast volumes of dust. It is to be confidently expected that Pre-Cambrian loesses will be found.

Clay in the form of small particles of sand dimension locally forms dunes. In an occurrence near the mouth of the Rio Grande[221] the clay is derived from mud-cracked surfaces of lagoons and deposited northwest of the source to form ridges several miles long, 200 to 300 yards wide, and 20 to 30 feet high.

THE "RED BEDS"

The "Red Beds" constitute a group of strata which have wide distribution over the Rocky Mountain region from Montana to Arizona and eastward to the Black Hills and central Oklahoma, and over parts of western and central Europe. They range in age from at least the Pennsylvanian to the Triassic, but similar deposits are found in many systems in some part of their distribution. Because of the wide extent of the "Red Beds," their considerable thickness, and the extensive consideration accorded them in geologic literature, they are given separate treatment apart from sediments of other colors.

The "Red Beds" are largely sandstones and silts and sandy shales, but they contain beds of gypsum, limestones, and dolomite which, considering the association, are remarkable for purity and whiteness, although the strong impression made by the latter characteristic is perhaps partly due to contrast with the associated red strata. In western Wyoming, Branson[222] states, the gypsum is very pure and covers many thousands of square miles, with an average thickness of one foot. The gypsum beds are stated to thicken and thin remarkably within short distances, the range being from a few inches to 40 feet. Many beds are shales, but these beds usually do not seem to contain a great deal of clay, the major portion of the rock being composed

[220] Newland, D. H., Recent progress in the study of the Salina formation, Rept. Comm. on Sedimentation Nat. Research Council, 1928, p. 38.

[221] Coffey, G. N., Dunes of clay, Jour. Geol., vol. 17, 1909, pp. 754–755.

[222] Branson, E. B., Origin of the Red Beds of western Wyoming, Bull. Geol. Soc. Am., vol. 26, 1915, pp. 217–230.

of small particles of quartz. Some "Red Beds" are coarse-grained sandstones containing feldspar and mica. The colors of the "Red Beds" are due to hematite or some other form of ferric oxide,[223] and many grains of quartz are coated with a film of the coloring materials. Some combined ferrous oxide may also be present. The quantity of each oxide, however, is usually not large, an analysis of the red rock of the Chugwater formation of the Wind River Valley of Wyoming giving 3.5 per cent ferric oxide and 1.04 per cent ferrous oxide.[224]

Fossils are rare in the "Red Beds," and marine fossils are generally wanting, but marine fossils do occur in some red strata.

The Sespe formation, a part of which forms the Tertiary "Red Beds" of the Pacific Coast, consists largely of sandstone and sandy shales with local conglomerates and rare and local beds of limestone. On the landward side of the time, that is, north, the colors range from reddish to deep brown. The typical "Red Beds" of the Sespe do not contain marine fossils, but toward the sea of the time, to the south, the colors change to gray, yellowish, and greenish and marine fossils are present.[225]

Wide diversity of opinion has existed and still exists with respect to the origin of the "Red Beds," particularly with respect to the conditions which permitted the development of the color. Some have held that the color developed or deepened subsequent to deposition, and Holland advanced the view that the red shales or clay so frequently associated with salt beds contained, at the times of deposition, much iron sulphide whose later oxidation imparted the red color. He states that no clays or silts with red colors are known in association with salt in process of deposition.[226] However, the weight of opinion has supported the view that the present colors of the "Red Beds" approximate those existing at the times of deposition.

The problems connected with the origin of the "Red Beds" may be divided into those concerned with the sources of the composing materials and the environments in which they originated, and those which have to do with the environments and agents of deposition.

Sources and Environments of Origin of the Materials Composing the "Red Beds"

Three hypotheses relating to sources have been advanced: namely, the materials were (1) produced through disintegration and partial decomposi-

[223] Dorsey, G. E., The origin of the color of the Red Beds, Jour. Geol., vol. 34, 1926, pp. 131–143.

[224] Tomlinson, C. W., The origin of the Red Beds, Jour. Geol., vol. 24, 1916, p. 161.

[225] Reed, R. D., Sespe formation, California, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 489–507.

[226] Holland, T. H., The origin of desert salt-deposits, Proc. Liverpool Geol. Soc., vol. 11, 1912, pp. 227–250.

tion of red granite or related rocks, (2) they were derived from pre-existing "Red Beds," and (3) they were derived from red residual soils.

The first hypothesis has application only in those cases where it can be shown that the constituents are such as could have been derived from granitic and related red rocks. Cross[227] has stated that the red color of the Dolores formation of the Rocky Mountain region is due partly to the pink grains of feldspar in the coarser layers, but even in this formation ferric oxide is chiefly responsible for the color. The red Triassic sandstones of eastern North America in considerable part owe their color to the red feldspar so abundantly present. However, as most of the "Red Beds" do not seem to contain a great deal of feldspar, this hypothesis has little application.

The hypothesis that the sediments were derived from pre-existing "Red Beds" does not yield a solution to the problem.

The third hypothesis gives a satisfactory source for the materials composing the "Red Beds." Red soils are formed on a considerable scale only in warm and moist, usually upland regions with good subsurface drainage, and such regions afford the only land environmental conditions making possible the accumulation of large quantities of red terrigenous materials. The quartz particles in the red soils of such environments are coated with ferric oxide in the same manner as occurs in the "Red Beds." Beede[228] suggested that the sediments which formed the "Red Beds" of eastern Oklahoma were derived from red residual soils of the Arbuckle and Wichita mountains of southern Oklahoma where such soils are now forming and Baker[229] seeks the same general source for the materials of the Permian Red Beds of Texas. Reed states that the mineralogy of the Red Beds of the Sespe formation suggests paleogeographic conditions for their formation like those of the southern Appalachian Mountains, and Tomlinson[230] concluded that the "development of ferruginous soils is the first prerequisite to the deposition of Red Beds of the western type," a conclusion with which most sedimentationists will probably agree. Streams are known to carry the red materials of these soils hundreds of miles without important change of color, as shown by the Red, Colorado, Brazos, and Pecos rivers of Texas.[231] If the particles are transported through and into environments wherein reduction of the iron is not favored and where there is not sufficient abrasion

[227] Cross, W., Telluride folio, No. 57, U. S. Geol. Surv., 1899, p. 2.

[228] Beede, J. W., Origin of the sediments and coloring matter of the eastern Oklahoma Red Beds, Bull. Geol. Soc. Am., vol. 23, 1912, pp. 723–724.

[229] Baker, C. L., Origin of Texas Red Beds, Bull. Univ. Texas, no. 29, 1916, pp. 1–8.

[230] Tomlinson, C. W., op. cit., p. 252.

[231] Baker, C. L., Non-arid genesis of American Red-Beds, Pan-Am. Geol., vol. 52, 1929, pp. 343–354; Depositional history of the Red Beds and saline residues of the Texas Permian, Bull. Univ. Texas, no. 2901, 1929, pp. 9–72 (26).

to remove the ferric oxide films, the red color would persist. Eolian transportation is not favorable for retention of color by the larger particles, as the ferric oxide would tend to be removed by abrasion; the effect on the smaller particles would be negligible and these would retain the red color. Aqueous transportation seems the more probable.

Environments and Agents of Deposition

The "Red Beds" have been assigned to a marine origin by some students,[232] and to a continental origin by others.[233] Some students have postulated deposition under marine conditions for parts of the "Red Beds" and deposition under continental conditions for other parts.[234] Other students have suggested the delta environment.[235]

The assignment to origin in a marine environment has very largely been based on the occurrence of beds of limestone, dolomite, and gypsum, the occasional presence of marine fossils, and the lateral gradation into marine beds. Branson[236] suggested the presence of good sorting, thin and persistent bedding, and ripple marks as evidences of marine origin, but no one of these characters or their aggregate is in any way conclusive, as the marine environment is not essential to their development. That sediments of red color are deposited in the marine environment is shown by the red clays and red muds of parts of the present sea bottom, but none of these sediments bears any close resemblance to the "Red Beds." There are sediments deposited in marine environments which are physically like the "Red Beds," except that they are not red and they do carry marine organisms. Various horizons of the geologic column carry red sandstones and shales which contain marine fossils, but these strata are of limited extent and are not comparable to the "Red Beds."

[232] Branson, E. B., Origin of the Red Beds of western Wyoming, Bull. Geol. Soc. Am., vol. 26, 1915, pp. 217–230, Abstract, pp. 61–62; Fenneman, N. M., Geology of the Boulder District, Bull. 265, U. S. Geol. Surv., 1905, pp. 54–57; Butters, R. M., Permian or Permo-Carboniferous, Bull. 5, Colorado Geol. Surv., 1913; Henderson, J., The foothills formations of North Central Colorado, Bull. 19, Colorado Geol. Surv., 1920; Henning, K. L., Die Red Beds, Geol. Rundschau, Bd. 4, 1913, pp. 228–244; Baker, C. L., op. cit., 1929. It should be understood that the conclusions in each case apply only to the "Red Beds" studied.

[233] Tomlinson, C.W., op. cit. Tieje, A. J., The Red Beds of the Front Range in Colorado, Jour. Geol., vol. 31, 1923, pp. 192–207; Dorsey, G. E., op. cit., 1926, pp. 131–143; Raymond, P. E., The significance of red color in sediments, Am. Jour. Sci., vol. 13, 1927, pp. 234–251.

[234] Branson, E. B., Triassic-Jurassic "Red Beds" of the Rocky Mountain region, Jour. Geol., vol. 35, 1927, pp. 607–630; "Triassic-Jurassic 'Red Beds' of the Rocky Mountain region:" A reply, Ibid., vol. 37, 1929, pp. 64–75; Reeside, J. B., Jr., "Triassic-Jurassic 'Red Beds' of the Rocky Mountain region:" A discussion, Ibid., vol. 37, 1929, pp. 47–63.

[235] Horwood, A. R., The origin of the British Trias, Geol. Mag., vol. 47, 1910, pp. 460–463; Reeves, F., Geology of the Cement oil field, Bull. 726, U. S. Geol. Surv., 1921, p. 58.

[236] Branson, E. B., op. cit., 1927, and 1929.

It is thought that the materials of the "Red Beds" originated under moist and warm conditions, that transportation from the places of origin to the sites of deposition was accomplished mainly by streams, and that deposition occurred under conditions prohibitive to incorporation of much organic matter, that, unless deposition was very rapid, the regions of deposition were either different from those of origin, or they may have been the same as the latter, deposition occurring in a succeeding geologic interval following a change of climate, the red materials in the latter case having been produced in one geologic interval and deposited in another.

It is believed that the environment of deposition could not have been that of normal, shallow marine waters, because under such conditions sufficient organic matter would have been included to reduce the iron and eliminate the red color, as is known to have occurred in existing marine deposits, and as was pointed out by Dawson[237] over eighty years ago to be taking place in red sediments brought to, and deposited in, the waters of Pictou Harbor, Nova Scotia. The red color could only have been retained under conditions of such rapid deposition as to prevent the colonization of the bottom by organisms, thus limiting the quantity capable of incorporation in the sediments. This seems possible only at the mouth of a river under the conditions of the delta environment. Deposition may have occurred in standing bodies of water whose salinity or some other deleterious condition was of such character as to preclude the entrance of organisms. Probably some red beds were deposited in such waters. Other places of deposition may have been flood plains of aggrading rivers and deltas.[238] If the former were so dry that little organic matter could enter the waters to mingle with the sediments as they were being transported from the places of origin to the sites of deposition, the red materials would have been deposited over the deltas either as parts of the subaerial topset beds or as parts of the aqueous beds; and for the red color to be retained, conditions would have to be such as to preclude the entrance of much organic matter, this being accomplished over the subaerial part of the delta by rapid deposition or by conditions limiting the quantity of plant growth. Deposition of the red sediments over the subaqueous parts of the delta would necessarily have to be rapid, otherwise organisms would enter the environment and the red color would

[237] Dawson, J. W., On the colouring matter of red sandstones and grayish and white beds associated with them, Quart. Jour. Geol. Soc., vol. 5, 1849, pp. 25–30.

[238] The sediments covering the Yellow River plain of China are said to be yellow and Grabau states that the iron is thoroughly oxidized and would become red as the sediments became consolidated. If the plain were fed from upland regions covered with red soils, the sediments would be red from the beginning and a formation similar to the "Red Beds" would result. Grabau, A. W., Memoir of the Institute of Geol., Nat. Research Inst. of China, no. 7, 1929, p. 27.

be lost. Red sediments deposited over the flood plains of aggrading streams would lose the redness under conditions of lush plant growth, although it might be retained if deposition were rapid, thus checking plant growth. The redness would probably be retained if the climatic conditions were such as to permit plant growth not beyond the disposition-ability of the bacteria of the region. An extremely semi-arid to arid climate is not favored, as under such conditions lightness of colors tends to prevail due to the larger grains being rolled around by the wind, with consequent abrasion of the iron-oxide films, the abraded iron oxide subsequently being transported from the region as dust. Redness of sediments could persist only if they were rapidly deposited and such sediments would necessarily have to be brought into the region from a bordering one. An extremely wet climate, particularly if cool, would produce so much organic matter to be included in the sediments that reduction of the iron seems certain. The climatic conditions favoring the deposition of red beds, in continental environments, with retention of color, are thought to lie between the two extremes of semi-aridity and moderate wetness, the particular conditions necessary being functions of rates of deposition, cloudiness, temperature and probably other factors.[239]

Those "Red Beds" carrying marine fossils in sufficient abundance to prove the marine environment may have that environment conceded. "Red Beds" which interdigitate or grade laterally into marine deposits also may have the marine origin wholly or partially conceded. Where fossils are so notably absent as in many of the "Red Beds" of Montana and Wyoming, the Front Range of Colorado, and parts of the Permian of Kansas and Oklahoma, however, the postulate of a marine origin presents difficulty. The wide extent of gypsum and carbonate beds shows a submerged, nearly flat area subject to prolonged evaporation, but not necessarily a marine environment, as these materials develop in continental deposits, and the thickening and thinning described by Branson would harmonize with some continental environments. Likewise, the persistence of many of the beds composed of clastic materials shows the presence of an environment in which wide and uniform distribution was possible. It is the opinion of Branson, Reeside, and others that a marine environment with highly saline waters most nearly fulfills the conditions for the deposition of some of the "Red Beds" studied by them. However, there needs to be differentiated the environment in which beds recognizably marine were deposited and the environment of origin of the associated beds. The observations of the

[239] For a consideration of the climatic conditions permitting red sediment accumulation the reader should consult Raymond, P. E., The significance of red color in sediments, Am. Jour. Sci., vol. 13, 1927, pp. 234–251.

writer convince him that large portions of the "Red Beds" personally studied (Kansas, Oklahoma, Montana, and Wyoming) were deposited on delta plains and flood plains of regions with climates supporting a limited to moderate plant growth. Parts of the Chugwater formation of Montana and Wyoming and some parts of the Permian of Kansas and Oklahoma seem best interpreted as deposits of standing bodies of water, but the occurrence of these strata in the midst of a formation cannot possibly serve as a reason for assigning the entire formation to an origin in the marine environment.

There have been suggestions that the materials of the "Red Beds" originated under desert climates, and the tradition has developed that red colors indicate such conditions. There is little to support these suggestions. The hypothesis of eolian transportation has been advanced for "Red Bed" deposition, but this finds little support in any of the "Red Beds" with which the writer is familiar. Tieje[240] has thus explained the Lyons formation of the Colorado Front Range, and Reeside thus interprets parts of the "Red Beds" with which he is familiar.[241] Tieje considers the Fountain formation of Colorado to have been stream-deposited on a fan or flood plain, and the Lykins formation as the subaerial part of a delta. According to Reeves,[242] the "Red Beds" of western and central Oklahoma were deposited on the subaerial parts of a delta which was built eastward into the Pennsylvanian and Permian seas by rivers draining western land areas where the Rocky Mountains now are, and Ver Wiebe postulates the same source for the materials.[243] Reed interprets the "Red Beds" of the Sespe formation of California as having been deposited in a subsiding area "that was adjacent to, and northeast of, a shallow sea." The basin probably was "not continuously under water, but was watered by streams of large size" and there were times of extensive areas of mud flats. There is an absence of typical desert features. The red beds do not seem to be of marine origin and the red color seems to be primary.[244]

Lomas interpreted the British Triassic "Red Bed" and associated strata as having developed under desert conditions.[245] Tomlinson's[246] general conclusion is that the "Red Beds" were deposited in a subaerial environ-

[240] Tieje, A. J., op. cit., pp. 198–202.
[241] Reeside, J. B., Jr., op. cit., 1929.
[242] Reeves, F., op. cit., p. 58.
[243] Ver Wiebe, W. A., Ancestral Rocky Mountains, Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 785–786.
[244] Reed, R. D., op. cit., pp. 505–506.
[245] Lomas, J., Desert conditions and the origin of the British Trias, Geol. Mag., vol. 44, 1907, pp. 511–514, 554–563.
[246] Tomlinson, C. W., op. cit., pp. 250–253.

ment in which fluvial deposition was most important, the deposition taking place under climatic conditions which were semi-arid or at least less humid than the places where the sediments originated. The Rotliegende of Germany seems generally to have been ascribed to a continental or subaerial origin.[247] Reeside's[248] statement that "a single explanation of origin seems entirely inadequate to account for all red beds" recognizes the probability, and it may be considered axiomatic, that clastic sediments of red color may develop in response to the conditions of several environments.

Sediments Dominantly Calcareous (Limestones)[249]

The per cent of calcium carbonate or the double carbonate of calcium and magnesium in sedimentary rock ranges from nothing to approximately 100. If the per cent equals or exceeds 50, the rock may be termed a limestone. If the per cent is below 50, the rock should be assigned to some other group. There is, however, no sharp division between limestones and other sedimentary rocks; they grade without sharp break into the sandstones and shales, as well as nearly every other variety of rock. The limestones are few which do not contain some sandy or clayey material, and, on the other hand, there are few mudstones, siltstones, and sandstones which do not contain some calcareous matter.

Limestones are composed either of calcite or dolomite. Those dominantly composed of the former are the calcitic limestones. Those whose dominant mineral is dolomite are dolomites or dolomitic limestones. Many calcitic limestones contain more or less dolomite, and many contain some magnesium carbonate which may not be in the form of dolomite but present as magnesite. Where the quantity is important, the rock may be called either a dolomitic or magnesian limestone, depending on the form in which the magnesium carbonate occurs.

In the deposition of $CaCO_3$ by physico-chemical agencies from waters containing magnesium, some of the latter is apt to be precipitated as magnesium hydroxide,[250] thus accounting for the small particles of dolomite which are common in many calcitic limestones. Calcium carbonate is deposited both as calcite and aragonite. Aragonite is deposited by waters of hot springs, from strongly saline waters, when an isomorphous car-

[247] Harrassowitz, H., Die Permformation, in Salomon, Grundzüge der Geologie, Bd. 2, 1926, pp. 287–292.

[248] Reeside, J. B., Jr., op. cit., p. 49.

[249] An up to date work on "Limestones, Their Origins, Distribution, and Uses," is that of F. J. North, London, 1930. The consideration of the origin of limestones is not exhaustive.

[250] Johnston, J., The solubility constant of calcium and magnesium carbonate, Jour. Am. Chem. Soc., vol. 37, 1915, p. 20.

bonate is present to serve as a nucleus,[251] and by organisms. The mineral is not stable and ultimately alters to calcite.

Although long studied, the precipitation of lime salts from sea water, except as directly brought about by organic agencies, is not well understood. Neither are data known permitting quantitative statement of the proportion due to organic origin. Sea water is a very complex solution. Under some conditions it precipitates lime salts, under other conditions it dissolves them, and under still others it neither precipitates nor dissolves. The reasons for these different actions are only partly known.[252]

LIMESTONES (CALCITIC LIMESTONES)

Pure limestones are white to gray, but as most of them contain substances other than calcite there is a great variety of color. Impurities in the form of iron oxide give yellow to red colors, and many limestones of light colors on fresh fracture become tan or buff on exposure, due to the oxidation of the ferrous iron which they contain. Limestones containing carbon, hydrocarbons, or carbonaceous substances range from blue to black; the presence of several silicates gives greenish colors. Most limestones contain small particles of quartz. This seems to be mostly of detrital origin, but in some may be a precipitate from solution or from colloids. Small crystals of pyrite or marcasite are also very common in limestones.

Limestones range in texture from those so extremely fine-grained as to break with conchoidal fracture and to show no macroscopic grains, to those which have the particles plainly visible. Some are entirely crystalline; others show few traces of crystals; and the two extremes may occur in the same section and the same beds. In some instances limestones are composed almost entirely of shell fragments, whereas in others no traces of organic remains are determinable. The former are not particularly common, and most shell limestones consist of shells imbedded in crystalline calcium carbonate, which cannot be referred to organic origin, but which may have resulted from attrition of organic calcium carbonate by organic and inorganic agencies, or was originally precipitated as finely divided calcium carbonate.[253] In general, it appears that macroscopically determinable organic matter constitutes the minor portion of most limestones. A feature observed in several seemingly pure calcitic limestones is the presence of ellipsoidal particles of the order of magnitude of small oolites. These are composed

[251] Johnston, J., and Williamson, E. D., The rôle of inorganic agencies in the deposition of calcium carbonate, Jour. Geol., vol. 24, 1916, p. 749.

[252] Vaughan, T. W., The oceanographic point of view, Cont. Marine Biology, Stanford Univ. Press, 1930, pp. 40–42.

[253] Goodchild, J. G., The paste of limestones, Geol. Mag., vol. 27, 1890, pp. 73–79.

of clay and broken calcite fragments and are interpreted as coprolitic. Many shales are highly calcareous, and many of these contain authigenic fully developed calcite crystals.

Limestones occur in every geologic system since the beginning of the Cambrian as formational units, interbedded with shales and dolomites, and in some instances interbedded with sandstones. It is theoretically possible for every gradation from limestone into shale and sandstone to occur. The Pre-Cambrian limestones are mainly dolomites, and such is also the case for many of the limestones of the early Paleozoic, the ratio of calcite to dolomite in limestones increasing from the Pre-Cambrian to Recent.[254]

$CaCO_3$ in Modern Deep Sea Sediments

Table 46, compiled by Vaughan[255] from the "Challenger" Report on modern deep-sea sediments, shows that calcium carbonate constitutes nearly one-third of such sediments. Murray and Renard state that the average $CaCO_3$ content of the deep-sea sediments is 37 per cent, of which fully 90 per cent is derived from pelagic planktonic calcareous organisms. Reducing Vaughan's figure, 32.20 per cent, to the oxide, gives 18.03 per cent. The per cent of calcium oxide in the earth's crust is given by Clarke[256] as 5.10, so that the percentage in modern deep-sea sediments is 3.53 times as great as in the crust of the earth. This concentration in the deeper water sediments must be balanced somewhere in other deposits; the sediments with a deficiency of lime may be those of the continental and delta environments. It is also possible that in the Paleozoic and older eras, before the advent of numerous pelagic planktonic calcareous organisms, the deep-sea sediments may have been low in $CaCO_3$, whereas in the later geologic periods the great abundance of these organisms led to great deposition of lime in the deep sea.[257] It has also been suggested that the excess of lime in sedimentary rocks may be due in part to its elimination from rocks during their anamorphism,[258] but the writer prefers to relate this abundance to the concentration of lime in the shallow-water deposits of past geologic periods and the transportation of large quantities of alumina, silica, and ferruginous materials to the deep seas of those periods.

[254] Daly, R. A., The evolution of the limestones, Bull. Geol. Soc. Am., vol. 20, 1909, p. 165.

[255] Vaughan, T. W., Oceanography in its relations to other earth sciences, Jour. Washington Acad. Sci., vol. 14, 1924, p. 313.

[256] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 34.

[257] Twenhofel, W. H., Magnitude of the sediments beneath the deep sea, Bull. Geol. Soc. Am., vol. 40, 1929, pp. 385–402.

[258] Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 67–68, 271–273.

The lime in the deep-sea sediments represents the difference between solution and the quantity of calcareous matter precipitated from the time

TABLE 46

(1) NAME OF DEPOSIT	(2) AREA IN SQUARE MILES	(3) PER CENT OF AREA OF EARTH	(4) PER CENT OF $CaCO_3$	(5) PRODUCTS OF FIGURES IN COLUMNS 3 AND 4
Red clay	51,500,000	26.2*	6.70*	175.54
Radiolarian ooze	2,290,000	1.1	4.01	4.41
Diatom ooze	10,880,000	5.5	22.96	126.28
Globigerina ooze	49,520,000	25.2	64.47	1,624.64
Pteropod ooze	400,000	0.2	79.25	15.85
Coral mud and sand	2,556,000	1.3	85.53	111.19
Volcanic mud, Volcanic sand	600,000	0.3	24.62	7.39
Green mud, Green sand	850,000	0.4	37.65	15.06
Red mud	100,000	0.05	32.28	1.61
Blue mud	14,500,000	7.3	12.48	91.10
		67.55		2,173.07

* Steiger states that the $CaCO_3$ in red clay is about 9 per cent.

$\frac{2173.07}{67.55} = 32.20$, average per cent of $CaCO_3$ in modern deep sea sediments.

TABLE 47*

DEPTH IN FATHOMS	AVERAGE PERCENTAGE OF $CaCO_3$
14 cases under 500	86.04
7 cases from 500–1000	66.86
24 cases from 1000–1500	70.87
42 cases from 1500–2000	69.55
68 cases from 2000–2500	46.73
65 cases from 2500–3000	17.36
8 cases from 3000–3500	0.88
2 cases from 3500–4000	0.00
1 case over 4000	Trace

* Murray, J., and Renard, A. F., Deep sea deposits, 1891.

of origin to that of deposition, whence it follows that such deep-sea sediments as the red clay and radiolarian ooze would average low in lime, this lowness being correlated with greater depth. Table 47 gives this relation of $CaCO_3$

to depth of water. Correns[259] has surmised that the extent of solution on the ocean bottom is related to renewal of the waters of those bottoms by currents, thus explaining why some parts of the deep ocean bottom suitable for lime deposition are low therein; and his diagrams show that in the deep waters far from land, lime deposition is not only proportional to depth, but also to the extent of bottom currents.

Origin of Limestones

Limestones are mostly of non-terrestrial deposition, the sea, and to a less extent, the lakes and rivers being the places or origin, but they are also deposited on lands not covered by bodies of water. The shallow sea is probably the place of the most extensive deposition of lime. Calcium carbonate is deposited also in deep water, but there is little evidence that the limestones of the geologic section originated under such conditions. The facts indicate that all important limestones of a high degree of purity are shallow-water or only moderately deep-water deposits, the most important factor in formation under favorable bottom and temperature conditions being not the depth of water, but the outwash of siliceous, aluminous, and ferruginous materials from the land.[260]

Limestones are produced by mechanical, and organic and inorganic chemical processes. Those of organic origin are either accumulations of shelly matter which formed parts of organic supporting or protective structures, or were precipitated as a consequence of certain vital activities of organisms, or from chemical processes initiated through decay of organic matter. Limestones of chemically inorganic origin result from changes in the conditions of water in which calcium salts are dissolved, from agitation of water, or from evaporation.

Most limestones probably develop from matter carried in solution. Limestone probably forms at times from finely divided calcium carbonate (some of which may be of colloidal dimensions) carried in suspension. Locally, limestone sands and larger particles are transported and deposited. The agent of transportation is mostly water, but limestones are known which developed through eolian transportation and deposition.

[259] Correns, C. W., Anzeichen von Beziehungen zwischen Strömungen und Bildung küstenferner (eupelagischen) Sedimente (Beobachtungen auf der deutschen Atlantischen Expedition, etc.). Neues Jahrb. f. Min., etc., Beil.-Bd. 57, 1928, pp. 1109–1117; Pratje, O., Berichte über die geologischen Arbeiten auf den Profilen VI bis VIII, Die deutsche Atlantische Expedition auf den Vermessungs- und Forschungschiff "Meteor," Zeits. d. Gesell. f. Erdkunde, Berlin, 1927.

[260] Vaughan, T. W., Oceanography in its relation to other earth sciences, Jour. Washington Acad. Sci., vol. 14, 1924, p. 328.

A classification of origins may be made as follows:

(A) Limestones directly or indirectly resulting from organic processes.
   (1) Developed through the accumulation and cementation of protective and supporting structures of organisms.
   (2) Developed through the vital activities of organisms.
      (a) Photosynthesis of plants.
      (b) Bacterial processes.
(B) Limestones of chemically inorganic origin.
   (1) Developed as a result of changes of conditions in water containing calcium carbonate in solution.
   (2) Developed as a result of evaporation.
(C) Limestones of mechanical origin.

(A) LIMESTONES FORMED FROM THE ACCUMULATION AND CEMENTATION OF PROTECTIVE AND SUPPORTING STRUCTURES OF ORGANISMS. The shells and supporting structures, in the deaths of the organisms which formed them, either accumulate in place or undergo some transportation. Ultimately most of the shells and other structures become broken by various organisms and wave and current action, and experience more or less solution. Calcium carbonate of this origin is deposited to a large extent in the sea, to a less extent in lakes, and to some extent in the rivers and on the land.

Recent limestones very largely composed of shells and shell fragments of macroscopic dimensions are known as *coquina*. The name should be extended to include similar limestones no matter what the position in the time scale.[261] Some recent limestones are composed of organic fragments of sand dimensions. These are more or less common on some tropical beaches and over adjacent inland areas to which winds transport sands of beach origin.

Shells of organisms consist chiefly of four substances, which, named in the order of probable abundance, are calcium carbonate, magnesium carbonate, silicon dioxide, and calcium phosphate. Ordinarily silicon dioxide and calcium phosphate are of little importance, but the former is the major constituent of siliceous sponges, radiolaria, and diatoms; and the latter holds a similar importance in the shells of phosphatic brachiopods and bones of vertebrates,[262] and is of considerable importance in the shells of some crustaceans. Calcium carbonate is by far the most abundant of the materials used in shells.

Organisms form their shells from salts in solution in the waters in which

[261] Kindle, E. M., Nomenclature and genetic relations of certain calcareous rocks, Pan-Am. Geol., vol. 39, 1923, pp. 367–368.

[262] Rogers, A. F., Mineralogy and petrography of fossil bone, Bull. Geol. Soc. Am., vol. 35, 1924, pp. 535–556.

they live, from those which are in their food, and perhaps to some extent from materials in suspension or in the muds and sands which in certain forms pass in large quantities through the alimentary tracts. Experiments by Murray and Irvine[263] have shown that it is not essential for the calcium required by animals to be in the form of the carbonate, but that calcium sulphate and some other calcium salts are readily utilized.

The lime salts in solution are mostly the carbonate, the bicarbonate, and the sulphate, the carbonates dominating in land waters in the ratio of about 10 to 1, and the sulphate dominating in ocean waters in about the same ratio. The bicarbonate is more abundant than the carbonate, as the latter is not very soluble in water in which carbon dioxide is not present, one liter of sea water free from carbon dioxide at 16°C. dissolving only 0.0131 gram per liter. If water contains carbon dioxide, this is supposed to unite with the carbonate to form the more soluble bicarbonate. The quantity of carbon dioxide in waters is thus a matter of great importance.

Carbon dioxide in water is thought to be largely combined with various bases in the form of carbonates and bicarbonates. Some may, however, exist "free." According to Wells,[264] the total quantities of carbon dioxide possible at 1°C. and 28°C., with the partial pressure of the atmosphere at 0.000318, are 0.101 gram per liter and 0.078 gram per liter respectively. Wells' determinations of the carbon dioxide in the waters of the Gulf of Mexico show at the surface an average of 0.092 gram per liter and a small increase with depth, the range for all depths being from 0.088 gram per liter to 0.100 gram per liter. The average for all depths was determined to be 0.094 gram per liter. The "free" carbon dioxide in these waters seems to be small. The results of Wells' determinations are of the same order of magnitude as those of earlier investigators.[265] The essential equality of the quantity of determined carbon dioxide in sea waters with that possible for the conditions indicates that approximate equilibrium with atmospheric carbon dioxide exists.

The quantity of carbon dioxide is inversely related to fall and rise of temperature, and, as the solubility of calcium carbonate (and other carbonates) is dependent so largely upon carbon dioxide, it follows that the colder waters of the ocean, that is, the deeper and polar waters,

[263] Murray, J., and Irvine, R., On coral reefs and other carbonate of lime formations in modern seas, Proc. Roy. Soc. Edinburgh, vol. 17, 1889–1890, pp. 79–109.

[264] Wells, R. C., New determinations of carbon dioxide in waters of the Gulf of Mexico, Prof. Paper 120-A, U. S. Geol. Surv., pp. 3, 5, 1918. No. 1 of the table is disregarded.

[265] Buchanan, J. Y., and Dittmar, W., Challenger Rept., Physics and Chemistry, vol. 1, 1884, p. 215; Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 146; Ruppin, E., Die Alkalinität des Meerwassers, Zeits. anorg. Chemie, vol. 66, 1910, p. 122.

should contain more dissolved calcium carbonate than those which are warmer.

Current views on the origin of the atmosphere relate its constituents to exhalations from volcanoes and associated phenomena. Under this hypothesis it seems probable that early Pre-Cambrian atmospheres were rich in carbon dioxide and low in oxygen. The evidences and supporting arguments for an atmosphere of such composition have been presented by Chamberlin,[266] Lane, Barrell, MacGregor, and others, these being mainly the relative absence of limestone in Archeozoic rocks, the high quantity of iron carbonates and silicates in Pre-Cambrian strata, the postulated relative richness of sediments in ferrous iron (Macgregor), and the absence of oxygen but presence of carbon dioxides and other atmospheric gases enclosed in pores of igneous rocks. The great quantities of carbon and carbon dioxide locked up in the sedimentary rocks, estimated to be equivalent in carbon dioxide to as much as twenty-five times the mass of the present atmosphere, prove probable variations of atmospheric content in this constituent.

If Pre-Cambrian atmospheres were as thus postulated, the waters would have been highly charged with carbon dioxide, and large quantities of calcium, magnesium, and iron and other carbonates would have been held in solution until agents or conditions developed to cause precipitation. In the absence of shell-forming organisms and other organic lime-precipitating agencies, the lime and magnesia, and also the iron, would remain in solution in large quantities. This may explain the scarcity of limestone formations in the Archeozoic, and assist in explaining the abundance of iron carbonates and iron silicates in the Pre-Cambrian rocks in general. The advent of green plants led to the breaking down of carbon dioxide, the fixing of carbon in the rocks, and the partial release of oxygen to the atmosphere. As the extraction of the carbon dioxide was done by plants, rapid precipitation of the carbonates of lime and magnesia must have been initiated and thus arose the great limestone formations of the Proterozoic.

The range of important constituents in shells of the different groups of marine invertebrates and calcareous algæ[267] is given in table 48.

Table 48 shows that limestones formed from shells of madreporarian and hydroid corals, annelids, most bryozoans, most brachiopods, and any of the mollusks are composed essentially of calcium carbonate, whereas lime-

[266] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 2, 1907, pp. 93–98, and subsequent works by Chamberlin; Lane, A. C., Lawson's classification of the Pre-Cambrian Era, Am. Jour. Sci., vol. 43, 1917, pp. 42–48; Barrell, J., Chap. I in "The Evolution of the Earth and its Inhabitants," 1918; MacGregor, A. M., The problem of the Precambrian atmosphere, South African Jour. Sci., vol. 24, 1927, pp. 155–172.

[267] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates, Prof. Paper 124, U. S. Geol. Surv., 1922.

TABLE 48

CLASS	$CaCO_3$	$MgCO_3$	SiO_2	$Ca_3P_2O_8$	$(AlFe)_2O_3$	$CaSO_4$
Foraminifera	77.02–90.11	1.79–11.22	Trace–15.33	Trace	Trace–4.94	0
Calcareous sponges	71.14–84.96	4.61–14.10	Trace– 7.81	?–9.96	Trace–5.72	0
Madreporaria	97.57–99.95	0.09– 1.11	0 – 1.25	Trace	0–0.74	0–0.21
Alcyonaria	72.99–98.93	0.35–15.73	0 – 1.70	Trace– 8.57	Trace–1.01	Trace–5.43
Hydroids	96.77–99.63	0.22– 1.28	0.02– 0.24	Trace	0.05–0.21	0.06–1.80
Annelids	89.66–91.55	0 –9.72	0	Trace– 0.99	0	Trace–0.13
Crinoids	83.13–91.55	7.86–13.74	0.02– 5.73	Trace– 1.44	0.08–1.41	0–1.44
Echinoids	77.91–93.13	5.41–13.79	0.05– 9.93	Trace– 1.85	0.14–5.20	Trace–2.56
Starfishes	83.42–91.06	7.79–14.31	0.03– 2.47	0.21– 0.78	0.12–0.94	?–1.84
Brittle stars	79.37–92.70	6.61–14.95	0– 2.39	Trace– 1.14	0.11–3.47	Trace–4.17
Bryozoa	63.29–96.90	0.63–11.08	0.18–16.71	Trace– 2.68	0.12–2.25	1.32–2.83
Calcareous brachiopods	88.59–98.61	0.49– 8.63	0.06– 0.52	Trace– 0.57	0.04–0.48	0.36–1.72
Phosphatic brachiopods	1.18– 8.35	0.79– 6.68	0.50– 0.91	74.73–91.74	0.29–1.16	2.93–8.57
Pelecypods	98.74–99.87	0 – 1.00	0 – 0.36	Trace– 0.40	0.04–0.50	
Gastropods	96.84–99.95	0 – 1.78	0 – 2.19	Trace– 0.85	0.04–1.89	0–0.20
Cephalopods	93.76–99.50	0.16– 6.02	0 – 0.19	Trace	0.06–0.15	
Barnacles	95.53–97.73	0.75– 2.49	0.03– 2.12	0– 0.77	0.15–0.72	
Crustaceans	28.56–82.64	3.65–15.99	0 – 3.82	8.68–27.44	0.06–8.86	Trace–5.33
Calcareous algae*	73.63–99.21	10.93–25.17	0.02– 2.11	Trace– 0.43	0.01–1.62	0.03–1.39

* Halimeda gave as low as 0.02 per cent $MgCO_3$.

stones formed from shells of foraminifera, sponges, alcyonarian corals, and all of the echinoderms so far as analyzed may carry a considerable content of magnesium carbonate. Phosphatic limestones develop from the shells of some brachiopods and crustaceans. Limestones formed from calcareous algæ will be high in magnesia, and a small leaching of some of the calcium carbonate will yield a product approaching the composition of dolomite.

Some organisms have shells composed of calcite and others of aragonite. The data relating thereto are as follows:[268]

Calcite	*Aragonite*
Lithothamnium, Alga	Halimeda, Alga
Lithophyllum, Alga	Galaxaura, Alga
Polytrema, Foraminifera	Millepora, Hydromedusa
Corallium, Alcyonarian	Distichopora, Hydromedusa
Tubipora, Alcyonarian	Heliopora, Alcyonarian
Serpula, Annelid	Spirula, Cephalopod
Terebratula, Brachiopod	Sepia, Cephalopod
Argonauta, Cephalopod	
Balanus, Crustacean	

The shells of many mollusks are partly calcite and partly aragonite, the latter forming the inner pearly portion. According to Böggild[269] almost all salt-water forms consist of calcite and aragonite and fresh-water forms are mostly calcite. Existing materials of fossil shells do not afford a basis for determination of their original crystalline structure.

So far as studied, shells composed of aragonite are almost completely non-magnesian, and the small quantity present may be due to impurity or alteration. On the other hand, calcite shells may be either magnesian or not, and the general principle appears to be that magnesium carbonate associates itself only with calcite, with which it is partly isomorphous, and not with aragonite, which is of different crystalline form. This fact may have some bearing on the formation of dolomite. An important fact discovered in the Clarke and Wheeler studies is that the proportion of magnesium carbonate in shells "is dependent on, or determined by temperature." This is clearly shown in the analyses of crinoids and Alcyonaria, and is suggested by the analyses of foraminifera, crustaceans, and algæ, those of the warmer waters containing more magnesium than those of the colder waters. The contributions of different organisms to the formation of limestone are suggested in succeeding paragraphs.

Foraminifera. In modern seas foraminifera are responsible for globiger-

[268] Clarke, F. W., and Wheeler, W. C., op. cit., pp. 57–58.

[269] Böggild, O. B., The shell structure of mollusks, Mém. de l'Académie Royale des Sciences et des Lettres de Danemark. 1930, pp. 239–245.

ina oozes, and in ancient seas for parts of the chalk. Murray and Renard designate as globigerina oozes those deposits which contain over 30 per cent of the dead shells of foraminifera. The color of globigerina ooze ranges from white to brown, depending upon the nature of the other substances mixed with the shells. The prevailing color is milky white or rose far from land, and dirty white, blue, or gray near land. The texture is very fine-grained and homogeneous, and in tropical regions many foraminifera are visible to the eye. This is not often true, however, for oozes of temperate regions. In addition to foraminifera, shells of many other organisms may be present, among which mollusks, pteropods, and calcareous algæ are important. In the oozes collected by the "Challenger" expedition, the per cent of calcium carbonate ranges from 30.15 in 2575 fathoms to 96.80 in 343 to 425 fathoms, the average for all depths being 64.47 per cent. There is a decrease in the carbonate of lime content with increase in depth. The per cent of lime carbonate due wholly to the shells of foraminifera is estimated by Murray and Renard to range from 25 to 80, with an average of 53.10. An average of 2.13 per cent of this content is assigned to the bottom-dwelling foraminifera, and the major portion is referred to shells of pelagic forms living in the upper waters. On the deaths of their owners these shells sink, but because of passing into solution few attain depths exceeding 15,000 to 16,000 feet. Other materials of globigerina oozes consist of siliceous organisms ranging from 1 to 10 per cent, with an average of 1.64 per cent; mineral matter ranging from 1 to 50 per cent and averaging 3.33 per cent; and very fine material from 1.20 to 64.62 per cent, with an average of 30.56 per cent. The minerals and rocks identified in the ooze consist of feldspars, augite, olivine, hornblende, quartz, magnetite, volcanic glass, etc. The residue is identical with the materials in red clays and similar deposits. Chemical analyses of globigerina ooze are given in table 49.

The average mechanical composition of the 118 "Challenger" samples of globigerina ooze is given in table 50.

Globigerina oozes cover about 50,000,000 square miles of the bottom of the ocean and constitute one of the most extensive of deposits, being equaled only by the red clay. Of this area, 22,500,000 square miles are in the Atlantic, 14,800,000 in the Pacific, and 12,220,000 in the Indian Ocean.[270]

Foraminifera occur in the geologic column from perhaps the Cambrian to the present. It was not until the Mississippian, however, that their contributions became of moment, and the Bedford limestones of that system have shells of *Endothyra baileyi* as an important constituent. In the Pennsylvanian and Permian limestones *Fusulina* and allied forms are of common occurrence over the entire earth, many beds consisting almost entirely of

[270] Murray, J., and Renard, A. F., Deep sea deposits, 1891, pp. 213–223.

foraminiferal shells. In the basal Tertiary the widespread Nummulitic limestone of the Mediterranean region is locally in part almost entirely composed of the shells of *Nummulites*, and throughout the marine Tertiary everywhere foraminifera are present in all sediments deposited under environmental conditions permitting entrance of such shells.

TABLE 49

CHEMICAL ANALYSES OF GLOBIGERINA OOZES

	DEPTH	
	1450 fathoms	2200 fathoms
	per cent	*per cent*
SiO_2	1.83	10.37
Al_2O_3	1.00	3.75
Fe_2O_3	1.72	1.51
MnO_2		Trace
$CaSO_4$	0.73	0.58
$CaCO_3$	91.32	65.67
$Ca_3P_2O_8$	0.28	1.74
$MgCO_3$	0.30	1.33
Insoluble	1.82	12.23
Loss, ignition	1.00	2.82
	100.00	100.00

TABLE 50

	PER CENT
Pelagic foraminifera	53.10
Bottom-living foraminifera	2.13
Other calcareous organisms	9.24
Siliceous organisms	1.64
Minerals	3.33
Fine washings	30.56
	100.00

The chalk formations contain foraminifera and have been considered ancient equivalents of modern deep-sea foraminiferal oozes, in spite of the fact that foraminiferal shells in most cases constitute only a small part of the rock,[271] most of it being composed of finely divided calcareous material, best

[271] Jukes-Browne, A. J., and Hill, W., The Cretaceous rocks of Britain, vol. 2, Mem. Geol. Surv. U. K., 1903, p. 540.

interpreted as a chemical precipitate,[272] or, at any rate, only indirectly due to organic activity. There are several objections to this view. The shells other than foraminifera seem to belong very largely to benthonic shallow forms. The sequence of the chalks and associated strata bears evidence that the former did not form in depths of which the modern oozes are characteristic. The chalks are underlain and overlain by sediments which could not have been deposited elsewhere than in shallow water, and there is little or nothing in the structure of the chalk regions permitting the assumption that between the deposition of the subjacent sediments and that of the chalk there was sinking to depths approximating those in which modern globigerina ooze accumulates, nor is there evidence of a rising of the sea bottom to an approximately equal extent to permit deposition of overlying shallow-water strata. Also, the chalks of both Europe and America locally contain interbedded sandy and shaly strata, and the shells of organisms other than foraminifera are frequently large and thick, each characteristic implying shallow-water deposition.

The great chalk formations are best interpreted as having formed in a shallow-water environment under conditions which are not understood. In America the conditions were such as to make it difficult for the corals and the brachiopods to exist in the waters of chalk deposition, and terrigenous sediments were restrained from entering.

Foraminiferal shells may accumulate as abundantly in shallow as in deep waters. In the former they are apt to be masked by the accumulations of higher marine invertebrates, plants, and inorganic sediments. Where conditions are such as to prevent the entrance of the last, and the environments do not favor the existence of other organisms, but do permit the existence of foraminifera, the shells of the latter and chemical precipitates constitute the major part of any deposit made. This is the case over parts of the sea bottom of the West Indies, where the materials over shallow-water bottoms are largely fine calcareous oozes, known as drewite.[273] Grabau[274] has suggested that the "White Chalk" of western Europe, in its absence of stratification in some parts, and in its fineness and homogeneity, resembles loess formed in close proximity to the sea, as shown by the fossil marine organisms which it contains. The chalks of England and France have also been interpreted as deposits of seas surrounded by hot deserts of the Saharan

[272] Cayeux, L., Contribution à l'étude micrographique des terrains sédimentaires, Mém. Soc. géol. du Nord, vol. 2, no. 2, 1897, p. 518; Tarr, W. A., Is the chalk a chemical deposit?, Geol. Mag., vol. 62, 1925, pp. 252–264.

[273] Field, R. M., Investigation regarding the calcium carbonate oozes at Tortugas, and the beach-rock at Loggerhead Key, Year Book 18, Carnegie Inst. of Washington, 1919, pp. 197–198.

[274] Grabau, A. W., Principles of stratigraphy, 1913, pp. 577–578.

type.[275] Böggild[276] assumes that in the beginning the chalk contained very few aragonite particles and was almost entirely composed of particles of calcite. Thus there was no reorganization of the carbonate and the sediments retained their original consistency and did not form into a firm rock.

Sponges. Sponges usually do not occur in quantities sufficiently large to form sponge limestones, but the Archæocyathinæ reefs (interpreted by some paleontologists as sponges) in the Lower Cambrian of the Strait of Belle Isle, Australia, and other parts of the world constitute important limestone formations. In the White Jura of Swabia are massive structureless limestones and dolomites which have been shown to have been built largely by calcareous sponges. Because of their massiveness and resistance the reefs persist after surrounding rocks have been eroded away, thus forming in the Swabian Alps isolated crags and outliers, whose easy defense made them sites of medieval strongholds.[277] Elsewhere in the geologic column and in modern seas the contributions of sponges are incidental to those of other organisms.

Corals. Corals have formed reef masses of limestone and have contributed to limestone formation in many parts of the world and in every part of the geologic column since the late Ordovician. Coral reefs[278] consist, in part, of coral colonies plastered over each other, stratification being wanting, or at least very rude. At the reef margins the composing limestones interfinger or dovetail with surrounding sediments, which are stratified and may be muds, sands, gravels, or other calcareous deposits. Some corals, as the stromatoporoids, may completely cover extensive areas of the bottom, forming beds of coralline limestone whose laminations record periods of growth. The significance of these laminations in terms of geologic history is not known.

Each coral reef is the site of intense organic activity, and nearly every available spot is inhabited. The coral heads are attacked by boring animals, and the more delicate forms are devoured by fishes. The work of organisms and the grinding of waves reduce much shelly matter to sands and muds. These and organic matter fill the pockets and interstices between the coral

[275] Bailey, E. B., The desert shores of the chalk seas, Geol. Mag., vol. 61, 1924, pp. 102–116.

[276] Böggild, O. B., The shell structure of mollusks, Mém. de l'Académie Royale des Sciences et des Lettres de Danemark, 1930, pp. 239–245.

[277] Grabau, A. W., Principles of stratigraphy, 1913, p. 442.

[278] Cumings, E. R., and Shrock, R. R., Niagaran coral reefs of Indiana and adjacent states and their stratigraphic relations, Bull. Geol. Soc. Am., vol. 39, 1928, p. 599. These authors propose to use the term "bioherm" for the phenomenon generally known as reef. The term is also intended to include any calcareous deposit due to colonies of organisms. Thus there are crinoidal bioherms, etc.

growths, and ultimately a compact mass is formed. The great volume of decaying organic matter, the warmth of the water, and the wave activity over the reefs lead to strong diagenetic activity in the reef rock, and many reef limestones have been changed to dolomite. Reef limestones seem to have a high degree of purity, with an almost complete absence of insoluble matter.[279]

Corals are not the only contributors to coral-reef limestones; many other organisms add their stony secretions. According to Howe, algæ are of great importance, and at the Atoll of Funafuti the relative abundance[280] of the organisms composing the reef rock was found to be (1) *Lithothamnium*, (2) *Halimeda*, (3) foraminifera, and lastly (4) corals. Not uncommonly crinoids were important contributors to Paleozoic coral reefs.

The limestones surrounding coral reefs not infrequently are crystalline and may pass commercially as marbles. Ordinarily they incline away from the reef limestones at high angles, and with distance from the reefs the crystalline character is lost. Reefs cut by channels have extremely variable sedimentary conditions, and there is much lateral variation of sediments from the finest of lime muds to limestone conglomerates. Clastic materials of terrigenous origin may also be present. The sediments of the lagoon back of a reef are commonly extremely fine lime muds.

Reef limestones present interesting problems in stratigraphy. The reefs rise greater or less distances above bottom to a maximum of perhaps 150 feet. The reef barriers, the barrier flats, and the more or less protected lagoons give three different environments, and protected nooks and depressions on and in the barrier flat may afford a fourth. The strength and turbulence of currents between reefs give rise to much variation of bottom, with greater or less corresponding variations in faunas. The nooks and depressions on and in the barrier flat may contain organisms unlike those on the adjacent deeper bottoms, which, however, are of the same stratigraphic level. In a geologic section there is likelihood that the two occurrences would be assigned to sequential rather than contemporaneous relations. Stratigraphic breaks are certain to develop in reef rocks, as growth to the surface of the water may proceed more rapidly than rise of sea level. These stratigraphic relations, together with the high angles of inclination of strata surrounding reef limestones, and possible slumping as

[279] Judd, J. W., The Atoll of Funafuti, Roy. Soc. London, 1904, p. 370; Skeats, E. W., The chemical and mineralogical evidence as to the origin of the dolomites of Southern Tyrol, Quart. Jour. Geol. Soc., vol. 61, 1905, pp. 110–111.

[280] Howe, M. A., The building of "coral reefs," Science, vol. 35, 1912, pp. 837–842; Finckh, A. E., in Sollas, et al. The Atoll of Funafuti, Rept. of Coral Reef Committee Roy. Soc. London, 1904, p. 133.

consequences render the interpretation of coral-reef geology and bioherms, in general, rather complicated[281] (figs. 27–29).

Coral-reef rock has great development in the Silurian and Devonian systems of North America and Europe, the Jurassic of Europe, and the Tertiary of America. In the Silurian period there were extensive reefs across northern United States and southern Canada from the Gulf of St. Lawrence to Iowa, and in the Baltic region on the Island of Gotland and the western shores of Esthonia. The reefs of Gotland are particularly striking, as the rough, structureless masses of limestones are exposed on the coast in high

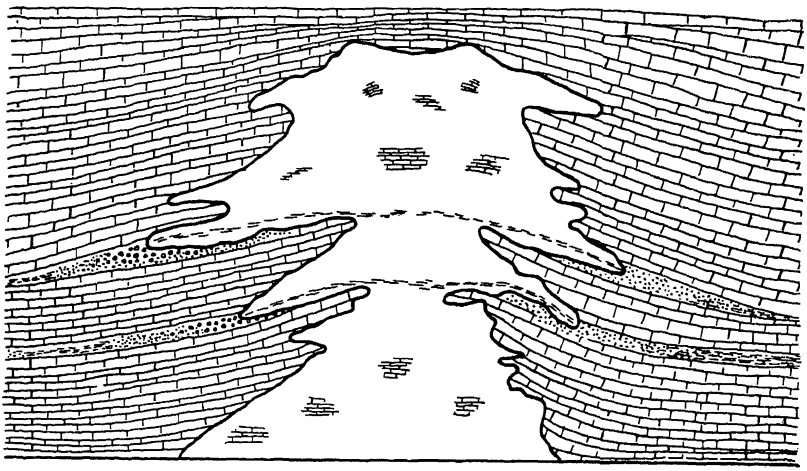

FIG. 27. DIAGRAM SHOWING RELATIONS OF CORAL-REEF AND ASSOCIATED ROCKS

Stratigraphic breaks may be assumed to exist just above the places where the reef has lateral spread, this being indicated by a shaly or sandy zone through the reef. Based on observations made on the reefs of Gotland, Anticosti, and eastern Wisconsin, and on the work of Munthe (The sequence of strata in southern Gothland, Geol. Fören. Stockh. Förhandl., Bd. 32, 1910, pp. 1397–1453) and others.

cliffs on the headlands. In the interior the resistance of the coral rocks as compared to the surrounding limestones and shales has left the former somewhat elevated above the surface. These elevations are known as klintar and are favorite sites for windmills. Elevations due to similar causes occur on the Niagara outcrop of northern Indiana.[282] The Silurian reefs of the Great Lakes region and the St. Lawrence embayment are in the Niagara and Monroe formations. The Niagara reef limestones of the Interior Basin,

[281] Grabau, A. W., Principles of stratigraphy, 1913, pp. 417–444. An excellent discussion of the geologic distribution of coral reef rock.

[282] Cumings, E. R., and Shrock, R. R., op. cit., 1928, p. 603.

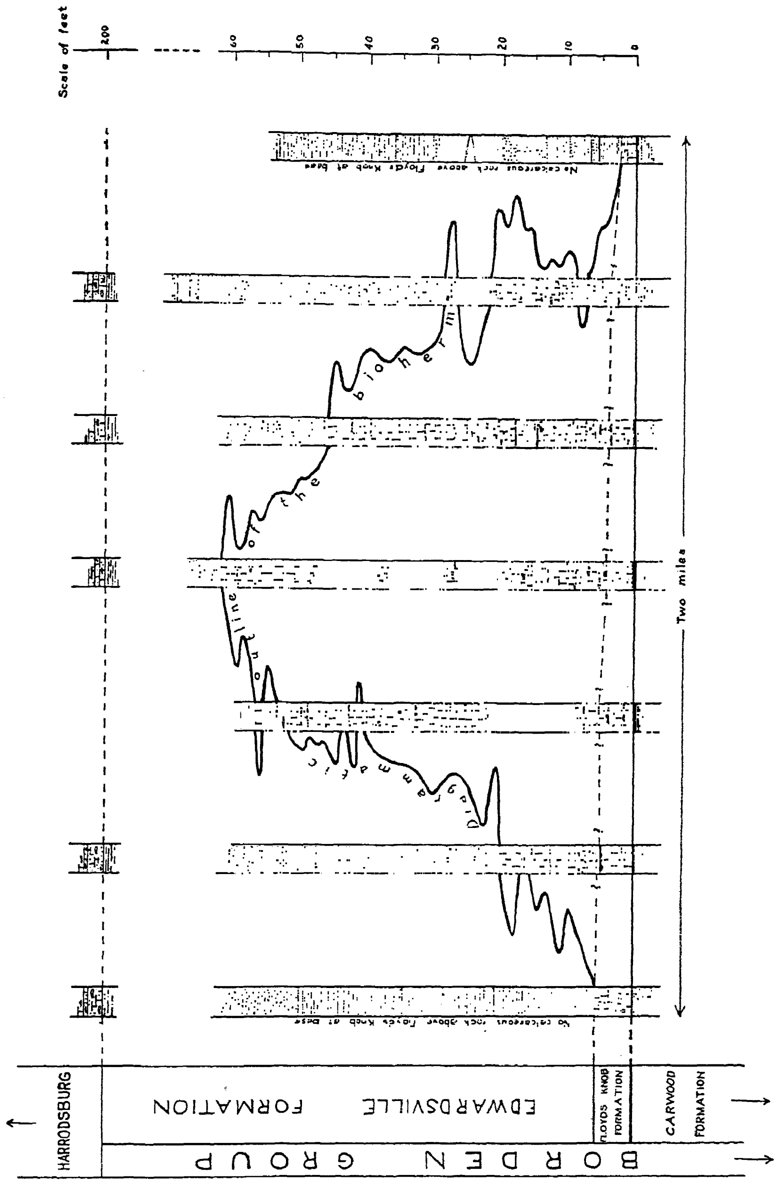

FIG. 28. DIAGRAM ILLUSTRATING A BIOHERM IN THE MISSISSIPPIAN STRATA OF INDIANA
Diagram by P. B. Stockdale, Bull. Geol. Soc. Am., vol. 42, 1931, fig. 2, p. 714

unlike those of Gotland and Anticosti, have been dolomitized, and much of the organic matter has been destroyed. The reefs of the Monroe are not nearly so extensive as those of the Niagara. The upper Wenlock of England contains ovoidal to lenticular masses of unstratified limestone, known as ball stones. These range to 90 feet in height, but are usually much lower, and are of limited lateral dimensions. The associated strata occasionally dovetail into the ball stones, but usually they end abruptly against them, and near the top, arch over them. The ball stones contain cyathophylloid,

FIG. 29. CORAL REEF AT HOBURGEN, GOTLAND

The white line shows the contact between the bedded crinoidal limestone on the left and the reef limestone on the right. The reef rests on oolite, and below the oolite is sandstone. The reef rock is over 100 feet thick. Photograph by Munthe, 1910.

favositoid, and stromatoporoid corals, together with cementing materials. Fossil organisms in positions of growth average 93 per cent; in the associated limestones only about 16 per cent are in natural positions. An interesting feature in connection with the ball stones and the associated limestones is that the former carry nearly ten times as much silica and seven times as much alumina as the latter and only about three-fourths as much lime.[283]

[283] Crossfield, M. C., and Johnston, M. S., A study of ball stone and the associated beds in the Wenlock limestone of Shropshire, Proc. Geologists Assoc., vol. 25, 1914, pp. 193–228.

The Silurian corals are mostly *Favosites, Halysites,* some of the Rugosa, and hydroids, the last usually being the most abundant. Algæ are generally present, but have not been shown to be abundant.

Devonian reef limestones occur in the Lower Devonian limestone of Bohemia, the Onondaga of New York, the Middle Devonian of Michigan, where the reefs average about 35 feet in height, the Middle Devonian of Iowa, the Eifel, and Belgium, and the Devonian of the Attawapiskat River, Canada. The corals mainly responsible for the Devonian reef limestones are stromatoporoids and colonial Rugosa, chiefly members of the Cyathophyllidæ.

Mississippian reefs are not known to exist in the American sequence, but reefs are present in the Mississippian of Belgium and possibly in Great Britain. The Pennsylvanian contains little reef limestone, although such is locally present, as in southern Kansas, where it is chiefly composed of *Chætetes milleporaceus* and colonial Rugosa.

The Jurassic reef limestones of Solenhofen in Bavaria and the associated lithographic stones (Plattenkalke) have been made famous by the exquisitely preserved and rare fossils which the latter contain. The thinly bedded lithographic stones lie in shallow basins surrounded by the non- or rudely stratified reef limestones, the two varieties of rock dovetailing into each other. The individual reef knolls suggest atolls, but the reefs as a whole seem to be best interpreted as marginal to Jurassic shores. The organisms composing the Jurassic reefs of central Europe are corals, chiefly *Ellipsactinia,* sponges, and mollusks.[284]

About coral reefs are muds and sands which are very largely derived from breaking and abrasion of the reef structures and the shells of other organisms which live on and about the reefs. The latter have been different at different times and places. Crinoids were abundant about many of the Paleozoic reefs, whereas about modern reefs the most abundant other organisms seem to be calcareous algæ and foraminifera. Laterally and outward from the reefs the muds and sands of this origin grade into other types of deposits. The muds have white to gray colors due to the large percentage of carbonate of lime present, this ranging in the "Challenger" samples from 89.68 per cent at 380 fathoms to 77.38 per cent in 1500 fathoms, the average for all depths being 85.53 per cent. Material other than lime carbonate ranges from 10.32 to 22.62 per cent and averages 14.47 per cent. This consists of clayey matter, oxides of iron, volcanic particles, siliceous tests of organisms,

[284] Berckheimer, F., Eine vorläufige Mitteilung über den Aufbau des Weissen Jura, etc., Jahresh. Ver. f. Naturk. in Württemberg, Jahrg. 69, 1913, pp. lxxvi–lxxxii; Walther, J., Die Fauna der Solenhofener Plattenkalke bionomisch betrachtet, Festsch. zum siebzigsten Geburtstage von Ernst Haeckel, Jena, 1904.

and mineral particles. The mechanical composition shows that foraminifera constitute a large portion. The average physical composition of coral muds and sands is as given in table 51.[285]

TABLE 51

	CORAL MUD	CORAL SAND
	per cent	*per cent*
Pelagic foraminifera	31.27	36.25
Bottom foraminifera	14.64	20.00
Other organisms	39.62	30.59
Siliceous organisms	1.36	5.00
Minerals	1.00	3.75
Fine washings	12.11	4.41
	100.00	100.00

The chemical composition of an average coral sand is as follows, the sample being taken at 18 fathoms off Tongatabu:

	Per cent
CaO	50.27
MgO	3.00
Al_2O_3, Fe_2O_3, P_2O_5	1.42
CO_2	42.28
Organic matter	2.78
Mn, Alkali, and SiO_2	trace
	99.75

Coral muds in open waters are deposited in somewhat greater depths than are coral sands. Coral muds of lagoons back of a reef are in shallower waters than the sands on the outer side.

Sediments of coralline and associated origins are found about all coral reefs of the world, the area covered by them being placed at 2,700,000 square miles. The greatest extent is in the Pacific region, with an area of 1,500,000 square miles. The Atlantic is estimated to have about 800,000 square miles and the Indian Ocean about 400,000 square miles. According to Collet,[286] the coralline deposits in the Indian Ocean have an area which is sixteen times that of the reefs.

Annelids. Annelids have not been important contributors to the formation of limestones. Some annelid material occurs in sediments from the Cambrian to the present, but the quantity in the Paleozoic and early Meso-

[285] Murray, J., and Renard, A. F., op. cit., p. 246.
[286] Collet, L. W., Les dépôts marins, 1908, p. 59.

zoic strata does not appear to be large. The serpulids made some contributions in the Cretaceous, and at the present time they make important deposits in certain tropical regions. In the Bermudas, for example, they are responsible for the formation of small atoll-like structures.[287]

Other reef-like bodies due to annelids are composed of sands cemented by tubes in which the worms live, the genus *Sabellaria* seeming to be the chief builder. The reef-like bodies approach coral reefs in dimension and their firmness is of course related to the abundance of the tubes. Reefs of sand cemented by *Sabellaria* form a barrier 3 km. wide and 10 km. long across one of the bays of Brittany in France.[288]

Echinoderms. The echinoderms are more or less colonial or gregarious, this statement applying in particular to the crinoids, blastoids, and echinoids, the most important of the limestone-formers. Analyses of shells show that some modern echinoderms carry an important percentage of magnesium carbonate. At the present time crinoids and echinoids live in colonies on parts of the sea bottom, where they must be forming sediments of which they constitute significant portions. During past ages crinoids, blastoids, and echinoids lived in great patches over parts of the sea bottom, where their remains formed crinoidal, blastoidal, and echinoidal limestones, such as the well known Pentremital limestones of the Mississippian system and the Crotalocrinus Kalk of the Silurian of the Oslo region. The Gotland section has a formation known as the Crinoidal limestone, and the Chicotte formation of the Anticosti section has some parts almost wholly composed of crinoidal remains. An interesting feature in connection with these crinoidal limestones is the fact that very commonly the color of some parts is red. Such is the case at Hoburgen on Gotland, on the Ringerike fiord in Norway, and in parts of the Anticosti section.

Bryozoa. Bryozoa have contributed to the formation of limestones since Middle Ordovician time. Most of the contributions have constituted minor additions, but at times bryozoans have grown in such large numbers as to form reef-like masses. Such are the reefs of bryozoa described by Sarle[289] and Grabau[290] from the Clinton and Niagara of New York. These reefs are frequently somewhat isolated, more or less spherical masses of limestone in

[287] Bullen, R. A., Some notes on the geology of the Bermuda Islands, Geol. Mag., vol. 48, 1911, pp. 385–395, 433–442.

[288] Richter, R., "Sandkorallen"-Riffe in der Nordsee, Natur und Museum, vol. 57, 1927, pp. 49–62. Review by Bucher, W. H., Am. Midland Nat., vol. 11, 1928, pp. 236–243.

[289] Sarle, C. J., Reef structure in Clinton and Niagara strata of western New York, Am. Geol., vol. 28, 1901, pp. 282–299.

[290] Grabau, A. W., Geology and paleontology of Niagara Falls and vicinity, Bull. 45, N. Y. State Mus. Nat. Hist., 1901.

the midst of other sediments, as exemplified by the reef in the Clinton of the Niagara Falls Gorge section. In forming the reef masses, bryozoans of more or less fan-like shapes lived on the bottom in colonies and captured sediments suspended in the waters which circulated about them, thus forming an impure limestone of which the bryozoan structures may constitute only a small part.

Brachiopods. Brachiopods have been important limestone-formers since the beginning of the Cambrian. They played a more important rôle in the Paleozoic than in subsequent times, although their contributions to the European rocks were important in the Mesozoic and Cenozoic. In the Paleozoic there are entire beds of limestone of which one or a few species of brachiopods and cementing calcite compose the whole. Such are the *Pentamerus borealis* Kalk and *Pentamerus estonus* Kalk of the Esthonian region, the *Pentamerus* limestones of the American Silurian, the *Productus* limestones of the Pennsylvanian, and the *Strophomena* and *Platystrophia* limestones of the Ordovician. As individual species, the most conspicuous limestone-formers were members of the Pentameridae, which at times covered the bottom of the sea with their shells to the almost total exclusion of other forms.

Mollusks. Mollusks have made contributions to formation of limestones from Middle Cambrian time to the present, although these organisms did not amount to a great deal before the Ordovician. Cephalopods and gastropods have rarely, and then only locally, dominated in the formation of a limestone. Certain limestones, as the Vaginaten Kalk of Esthonia and the Gastropoden Kalk of Norway, have received names from the presence of the characteristic fossils, but these organisms usually constitute only small portions of the formation. The coast of Florida has limestones known as "worm rock" which are very largely composed of the tubes of a species of gastropod known as *Vermetus nigricans.* This rock is being formed at present, and its formation goes back to Pleistocene times.[291]

Pteropods are responsible for a calcareous ooze attaining extensive distribution in modern seas. This ooze is composed of dead shells of pteropods and heteropods along with the shells of other pelagic mollusks or larval forms. Foraminifera are also present. Pteropod ooze is limited below by the depth of about 1500 fathoms, although shells of pteropods occur to depths of 2000 fathoms. Shoreward the ooze grades into other deposits, the pteropod shells being masked because of abundance of other sediments. Calcium carbonate in pteropod ooze ranges from 52.22 per cent at 900 fathoms to 98.47 per cent at 1240 fathoms, and the average is 79.25 per cent. The

[291] Matson, G. C., Second Ann. Rept., Florida Geol. Surv., 1909, pp. 154–155. Dall, W. H., Neocene of North America, Bull. 84, U. S. Geol. Surv., 1892, p. 15

average mechanical composition of the "Challenger" samples of pteropod oozes is given in table 52.

TABLE 52

	PER CENT
Pelagic foraminifera	47.15
Bottom-living foraminifera	3.15
Other organisms	28.95
Siliceous organisms	2.89
Minerals	2.85
Fine washings	15.01
	100.00

The following is a representative analysis of pteropod ooze from the depth of 450 fathoms:

	Per cent
SiO_2	4.14
Fe_2O_3	3.00
Al_2O_3	1.80
$CaCO_3$	84.27
$CaSO_4$	1.00
$Ca_3P_2O_8$	trace
$MgCO_3$	1.28
Loss on ignition	2.60
Insoluble	2.05
	100.14

Compared with globigerina ooze, pteropod ooze is more friable and granular, less homogeneous and uniform, and has a higher calcareous content.

The "Challenger" expedition found pteropod ooze in extensive areas only in the Atlantic Ocean, where it was met with in its most typical form on the central ridges to depths not exceeding 1400 fathoms. It is estimated to cover about 400,000 square miles of the bottom. Local occurrences of small area exist about some of the oceanic islands, and many tropical islands appear to be surrounded between the depths of 400 and 1400 fathoms by a deposit which might be called pteropod ooze.[292]

Pelecypod shells constitute large percentages of some limestones. In Jurassic and Cretaceous strata there are entire beds which are almost wholly made up of the shells of *Gryphæa* and *Exogyra*. Since the Cretaceous, oysters have been responsible for beds of limestone. Important beds of pelecypod limestones are the Champion and other shell beds in the Belvi-

[292] Compiled from Murray, J., and Renard, A. F., op. cit., pp. 223–228.

dere formation of Kansas, the *Gryphæa* beds of the Fredericksburg of Texas and Oklahoma, the *Exogyra* beds of the Taylor marl, and the *Ostrea* beds of the Eagle Ford shales. In the Plains Cretaceous are columns of shells in the midst of shale, the shells being mostly of the genus *Lucina*. As the shell accumulations are more resistant than the surrounding shale, they persist after erosion of the latter, forming "tepee buttes." Favorable places on the bottom of the Cretaceous sea permitted small colonies of shells to flourish. Other sediments accumulated around these colonies and generations of shells continued to build over the remains of their predecessors, the columns developing in this way.

Crustaceans. Crustaceans have made contributions to the materials of limestones since the beginning of the Cambrian. Their tests are generally present to some degree, particularly in early Paleozoic limestones, but they rarely constitute the major part of any stratum.

(A_2) LIMESTONES RESULTING FROM THE VITAL ACTIVITIES OF ORGANISMS. Limestones resulting from the vital activities of organisms are those produced by the photosynthesis of green aquatic plants, by bacterial activity, and perhaps in other ways. Limestones of this origin may form in both fresh and salt water.

($A_2(a)$) Limestones Resulting from the Photosynthesis of Plants. In photosynthesis, calcium carbonate is precipitated as an incrustation more or less over the surfaces of submerged plants, and in some plants also within cells and cell walls. Precipitation results from extraction of carbon dioxide from water by plants, and consequent reduction of the bicarbonate, followed by the precipitation of the latter in waters saturated therewith. As the carbon dioxide is taken from water immediately adjacent to those parts of the plant doing the extracting, it naturally follows that much of the precipitated material is deposited on plant surfaces, particularly those surfaces having considerable expanse. This type of work is done by every green plant living beneath a water cover.

It is probable that algæ do this work to the greatest extent, particularly those belonging to the Chlorophyceæ, or green algæ, and the Rhodophyceæ, or red algæ, the former including *Halimeda* and *Udotea* and the latter *Corallina, Jania, Melobesia, Lithothamnium,* and *Lithophyllum.* They range from the Tropics to Arctic regions and usually are abundant in all waters with favorable environments. In *Lithothamnium* the precipitate forms crusts over the surfaces on which the plant grows; the precipitate in *Halimeda* is a sieve-like cover about the tips of the algal filaments; and in *Acertularia* a tube is formed about the stalk of the plant. In *Chara* and the corallines the lime is deposited in the cells and cell walls of certain parts of the plants. The lime appears to form at first as tiny separate crystals,

which ultimately develop into star-like clusters, and these by enlargement unite to form solid masses or layers.[293]

The vertical range of the algæ seems greater than that of the reef-building corals, going down to 284 meters in the Caribbean;[294] ordinarily the range appears to be comprehended within less than 200 feet of the surface. The higher aquatic plants live close to the surface.

Lithothamnium is extremely abundant in northern latitudes, occurring in great abundance on the coasts of Norway and northern Newfoundland and no doubt elsewhere. In northern Newfoundland there are parts of shallow bottoms where *Lithothamnium* has formed a white coating over nearly everything. It is an extremely important contributor to coral reefs, and in the materials derived from the boring on Funafuti it was the most abundant organic substance. *Halimeda*, another alga, was second in abundance. In some waters this plant grows with great rapidity. In six weeks at Funafuti it had formed a cluster 55 mm. high and 80 mm. in diameter, the growth representing 14.38 grams of calcium carbonate.[295]

According to Howe,[296] coral reefs in large part are composed of algal materials, and these are quantitatively of greater importance than are corals. *Lithothamnium* is the principal reef builder in the Bermudas,[297] coral playing a secondary rôle, which is also the case in the Fiji reefs and those of the Chagos group of islands.[298] The materials of greatest quantitative importance in the reefs and reef sands of Pago Pago Harbor, Samoa, are those of the calcareous algæ, corals probably ranking second in importance.[299]

The leaves of all submerged aquatic green plants of fresh and other waters may become covered with calcium and other carbonate incrustations and many aquatic plants of lakes adjacent to Madison, Wisconsin, are thus

[293] Cohn, F., Die Algen des Karlsbader Sprudels mit Rücksicht auf die Bildung des Sprudels Sinters, Abh. d. Schlesischen Gesell. d. Naturwiss., Heft 2, 1862, pp. 35 et al.; Pia, J., Pflanzen als Gesteinbildner, 1926.

[294] Agassiz, A., Three Cruises of the "Blake," vol. 1, 1888, p. 141.

[295] Chapman, F., and Mawson, D., On the importance of Halimeda as a reef-forming organism: with a description of Halimeda-limestones of the New Hebrides, Quart. Jour. Geol. Soc., vol. 62, 1906, pp. 702–711: Finckh, A. E., The biology of the Funafuti Atoll, in Sollas, et al., The Atoll of Funafuti, Rept. Coral Reef Committee of Roy. Soc. London, 1904, pp. 145–146.

[296] Howe, M. A., The building of coral reefs, Science, vol. 35, 1912, pp. 837–842.

[297] Agassiz, A., A visit to the Bermudas in March, 1894, Bull. Mus. Comp. Zool., vol. 26, 1895, pp. 205–281.

[298] Gardiner, J. S., The coral reefs of Funafuti, Rotuma, and Fiji, together with some notes on the structure and formation of coral reefs in general, Proc. Cambridge Philos. Soc., vol. 9, 1898, pp. 417–503.

[299] Bramlette, M. N., Some marine bottom samples from Pago Pago Harbor, Samoa, Publ. 344, Carnegie Inst. Washington, 1926, pp. 6–7.

visibly coated. Analyses of *Chara* from Michigan lakes show over 0.61 grams of soluble mineral matter in the average plant, of which 94 per cent is calcium carbonate.[300] *Chara* from Green Lake, Wisconsin, has 41.22 per cent ash on sand-free, air-dry basis, of which 37.82 per cent is calcium oxide and 1.19 per cent magnesium oxide. The annual crop of *Chara* (dry weight) in Green Lake is about 800 tons per acre, equivalent to an annual deposition over the bottom from *Chara* alone of over 1000 tons of calcium carbonate,[301] or about 90 tons per square mile, giving a rate of deposition of one foot in about 2500 years. As *Chara* is about one-half the annual crop of the larger aquatic plants in this lake,[302] and in addition there are probably other sources of lime deposition, it suggests a rate of deposition for lime carbonate approximating 1 foot in 1000 years.

The quantity of calcium and probably other carbonates thus precipitated by plants is correlated with the quantity of carbonates in solution. Roddy[303] has shown that algal "concretions" do not form in Pennsylvania streams studied by him wherein the waters are low in calcium carbonate, whereas in the two streams in which "concretions" formed in abundance, Little Conestoga and Donegal creeks, the calcium carbonate content was high, ranging from 230 to 404 parts per million.

Davis has suggested that in waters very low in calcium some precipitation might take place as a consequence of release of oxygen by plants, the oxygen then reducing bicarbonate to carbonate, which would be precipitated. To what extent this takes place is uncertain,[304] but as pointed out by Johnston and Williamson,[305] the effect of the oxygen would be to sweep carbon dioxide from the water to the escape of which the precipitation would really be due. Carbonates precipitated by many living calcareous algæ are relatively high in magnesium carbonate, although dominantly composed of calcium carbonate. If such was the case during past geologic periods, a partial explanation is given for the characteristically dolomitic constitution of those formations high in algal material. Little is known, however, relating to American fossil algæ, and it is a field inviting research.

[300] Grabau, A. W., op. cit., p. 471.

[301] Schuette, H. A., and Alder, H., A note on the chemical composition of Chara from Green Lake, Wisconsin, Trans. Wisconsin Acad. Sci., vol. 24, 1929, pp. 141–145.

[302] Rickett, H. W., A quantitative study of the larger aquatic plants of Green Lake, Wisconsin, Trans. Wisconsin Acad. Sci., vol. 21, 1924, p. 381.

[303] Roddy, H. J., Concretions in streams formed by the agency of blue green algæ and related plants, Proc. Am. Philos. Soc., Philadelphia, vol. 54, 1915, pp. 246–258.

[304] Davis, C. A., Natural history of marl, Geol. Surv. Mich., vol. 8, pt. iii, 1903, pp. 65–96; A second contribution to the natural history of marl, Jour. Geol., vol. 8, 1900, pp. 485–497.

[305] Johnston, J., and Williamson, E. D., Jour. Geol., vol. 24, 1916, p. 739.

Algæ have been important limestone builders[306] since at least as early as the Huronian, and there are few formations of limestone since that time to which they have not contributed. It is, indeed, possible that they made limestone before the Huronian, Gruner[307] having described structures in rocks referred to the Archean which he assigned to algæ. Hawley's work, however, casts some doubt on this reference.[308] Algal materials form reef-like bodies in ancient dolomites, the Huronian Kona dolomite about Marquette, Michigan, being composed of large conical bodies with concentric structure. Algal deposits of greater extent have been described by Walcott[309] in the Huronian of the Rocky Mountains and by Moore[310] in rocks of the same age on the east shores of Hudson Bay. Seemingly similar structures in the dolomites of the Pre-Cambrian Campbell Rand series of South Africa have been referred to the action of pressure,[311] but there is little doubt in the writer's mind that algæ were responsible for their formation.

The Lower Ordovician dolomites of the Mingan Islands, upper Mississippi Valley, Big Horn Mountains,[312] and no doubt elsewhere have many beds largely composed of dome-shaped algal structures. The Oneota dolomite of southwestern Wisconsin records bottoms which seem to have been covered with dome-shaped algal growths ranging to 2 and 3 feet in diameter and a foot high, and the Mendota dolomite possesses similar structures of relatively narrower and relatively higher dimensions.

Material of algal origin is important in the great reefs of the Silurian of Gotland, and three members of the Gotland section have been named from characteristic genera of algæ. Algæ also occur in the Anticosti Silurian. The Ringerike section of Norway contains a limestone at the top of the Ordovician which seems to be largely composed of algal matter. Consider-

[306] Garwood, E. J., Calcareous algæ, Geol. Mag., vol. 40, 1913, pp. 492–495, 549–551; Important additions to our knowledge of fossil algæ since 1913, etc., Quart. Jour. Geol. Soc., vol. 87, 1931, pp. lxxiv-c. Glock, W. S., Algæ as limestone makers and climatic indicators, Am. Jour. Sci., vol. 6, 1923, pp. 377–408.

[307] Gruner, J. W., Algæ, believed to be Archæan, Jour. Geol., vol. 31, 1923, pp. 146–148.

[308] Hawley, J. E., An evaluation of the evidence of life in the Archean, Jour. Geol., vol. 34, 1926, pp. 441–461.

[309] Walcott, C. D., Pre-Cambrian Algonkian algal flora, Smithsonian Misc. Collections, vol. 64, No. 2, Publ. 2271, 1914.

[310] Moore, E. S., Algal limestone on the Belcher Islands. Jour. Geol., vol. 26, 1918, pp. 412–438. Abstract in Bull. Geol. Soc. Am., vol. 29, 1918, p. 128.

[311] Young, R. B., Pressure phenomena in the dolomitic limestones of the Campbell Rand series in Griqualand West, Trans. Geol. Soc., South Africa, vol. 31, 1928, pp. 157–165.

[312] Blackwelder, E., Origin of the Bighorn dolomite, Bull. Geol. Soc. Am., vol. 24, 1913, pp. 607–624.

able algal material is known to occur in the Carboniferous of both Europe[313] and America. The Permian of southern Kansas and northern Oklahoma contains many algal "concretions" in some beds, and in southwestern Texas the Permian Capitan limestone contains materials of algal origin,[314] and the great, more or less structureless masses in this limestone formation are best interpreted as algal reefs.[315] The reef bodies are very thick and wide and extend for many miles. On one side, the southeast, they are bordered by steeply dipping beds composed of materials partly interpretable as having washed from the reefs; on the other side the strata are less steeply inclined and composed of finer materials. The former side is considered that of the open sea. The limestones are dolomitic and some of them are oolitic.

The Triassic dolomites of the Tyrol contain reefs of which the chief organic remains are calcareous algæ and echinoderms. The reefs range to 3000 feet, but individually they seem to have limited extent in plan. Tongue-like extensions dovetail into associated rocks which commonly seem to be inclined outward from the reefs. On the northern sides of the reefs the algæ are delicately branching corallines, but on the southern side the plant structures seem to be coarser, and the cross lamination and interfingering suggest the exposed or seaward side. It seems to be generally agreed that the more or less structureless masses of dolomite are of reef origin,[316] with algæ being the most important contributors, and that their rocks are contemporaneous with the marginal stratified dolomites, but it has been held that the structureless bodies obtained their positions and characters as consequences of earth movements.[317]

As noticed on other pages, the Salt Lake oolites and the oolites of the Red

[313] Garwood, E. J., Rock-building organisms from the Lower Carboniferous beds of Westmoreland, Geol. Mag., vol. 51, 1914, pp. 265–271; The important part played by calcareous algæ in certain geological horizons, Ibid., vol. 50, 1913, pp. 440–446, 490–498, 545–553.

[314] Ruedemann, R., Coralline algæ, Guadalupe Mountains, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 1079–1080.

[315] Lloyd, E. R., Capitan limestone and associated formations of New Mexico and Texas, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 645–658; Crandall, K. H., Permian stratigraphy of southeastern Texas and adjacent parts of western Texas, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 935–937; King, P. B., and King, R. E., The Pennsylvanian and Permian stratigraphy of the Glass Mountains, Univ. Texas, Bull. 2801, 1928, pp. 139–140.

[316] Richthofen, F. von, Geognostische Beschreibung der Umgebung von Predazzo, St. Cassian und der Seisser Alpen in Süd Tyrol, Gotha, 1860; Mojsisovics, E. von., Die Dolomit-Riffe von Süd-Tirol und Venetien, Vienna, 1879; Skeats, E. W., On the chemical and mineralogic evidence as to the origin of the dolomites of the Southern Tyrol, Quart. Jour. Geol. Soc., vol. 61, pp. 97–141, 1905. Garwood, E. J., Calcareous algæ, Geol. Mag., vol. 50, 1913, pp. 492–495, 549–551.

[317] Ogilvie-Gordon, M., Contributions to the geology of the Wengen and St. Cassian strata of southern Tyrol, Quart. Jour. Geol. Soc., vol. 49, 1893, pp. 1–78.

Sea have been ascribed to an algal origin by Rothpletz.[318] Seward[319] states that the Great Salt Lake oolites are covered with the cells of *Glœocapsa* and *Glœotheca*, two genera of the Chroococcaceæ, and that sections of the oolites show these forms to be present in the interiors. The Red Sea oolites are said to show the presence of similar forms. From this it was concluded that the algæ were responsible for the deposition of the lime carbonate composing the grains. As noted in connection with the subject of oolites, the evidence is not convincing, and the presence of the algæ may be merely incidental.

Algal reefs have extensive distribution in the Green River Tertiary formation,[320] and oolites are associated. The tufas of the Lahontan basin also seem to be in part, at least, of algal origin.

Recent lime carbonate deposits of algal origin are common and may be seen about the shores and on the bottoms of the sea in many parts of the world. They have been described from the lakes of Michigan,[321] New York, Pennsylvania, Canada, and numerous other places. A rather remarkable occurrence from the point of view of abundance of the algal bodies has been described from southwestern Australia, where the algal balls or "biscuits" are forming in depressions which are dry during a part of each year. The "biscuits" range from tiny to 20 cm. in diameter, and some approach sphericity. The composing materials are calcite, with which may be a little magnesium carbonate[322] (fig. 30).

($A_2(b)$) *Limestones Resulting from Bacterial Processes.* It is possible that bacteria are important agents in precipitating the finely divided calcium carbonate which occurs over extensive parts of the shallow bottoms of the warmer portions of the sea. Drew[323] has suggested that denitrifying bacteria are important in the formation of the calcium carbonate which Vaughan

[318] Rothpletz, A., Über die Bildung der Oolithe, Bot. Centralblatt, vol. 51, 1892, p. 265.

[319] Seward, A. C., Fossil plants, vol. 1, 1898, pp. 122–123. Cambridge Univ. Press.

[320] Bradley, W. H., Shore phases of the Green River formation in northern Sweetwater County, Wyoming, Prof. Paper 140, U. S. Geol. Surv., 1926, pp. 125–126; Algæ reefs and oolites of the Green River formation, Prof. Paper 154-G, U. S. Geol. Surv., 1929, pp. 203–223.

[321] Pollock, J. B., Blue-green algæ as agents in the deposition of marl in Michigan lakes, 20th Ann. Rept., Michigan Acad. Sci., 1918, pp. 247–259; Clarke, J. M., The water biscuit of Squaw Island, Canandaigua Lake, N. Y., Bull. 39, N. Y. State Mus., 1900, pp. 195–198; Roddy, H. J., Concretions in streams formed by the agency of blue green algæ and related plants, Proc. Am. Philos. Soc., vol. 54, 1915, pp. 246–258; Kindle, E. M., The physical and biological characteristics of certain types of marlite balls from Manitoba and Michigan, Proc. and Trans. Roy. Soc., Canada, vol. 17, sec. 4, 1923, pp. 105–114.

[322] Mawson, D., Some South Australian algal limestones in process of formation, Quart. Jour. Geol. Soc., vol. 85, 1929, pp. 613–623.

[323] Drew, G. H., On the precipitation of calcium carbonate in the sea by marine bacteria, Papers from the Tortugas Lab., Carnegie Inst. of Washington, vol. 5, 1914, pp. 7–45. The works of Baur, Gran, Feitel, and Brandt are cited by Drew.

observed as constantly being precipitated at Tortugas, and of which McClendon observed the actual precipitation in the Marquesas lagoon at a time when the H-ion concentration was low.[324] Bacteria of this character have been identified in the Bay of Kiel by Baur, on the Dutch coast by Gran, in the open waters of the North Sea and the Baltic by Feitel and Brandt, in the Gulf of Mexico and elsewhere by Drew, and in Great Salt Lake by Kellerman and Smith.[325] The bacillus held responsible for the precipitation in the Gulf of Mexico and adjacent waters was named *Bacterium calcis* by Drew, but was subsequently shown to belong to the genus *Pseudomonas*. Cultures of this bacillus made by Drew indicated that it is capable of chang-

FIG. 30. ALGAL "BISCUITS" OF BISCUIT FLAT, SOUTHERN AUSTRALIA

The algal "biscuits" shown in the illustration form in shallow, inter-dune basins which may be covered with water to a depth of a few inches during wet seasons and are mostly dry during the dry seasons. The region is underlain by limestone and the waters are more or less salty. Blue-green algæ are held responsible for the formation of the "biscuits." Illustration taken from Sir Douglas Mawson's article in the Quart. Jour. Geol. Soc., vol. 85, 1929, pl. 37.

ing calcium nitrate to calcium carbonate, and he supposed a similar action to take place in sea water. This organism does not occur in abundance in the upper or surface waters, but seems to live in the muds of coastal waters, where as many as 160,000,000 per cubic centimeter were found in surface muds collected on the west side of Andros Island, and this was estimated

[324] Vaughan, T. W., Preliminary remarks on the geology of the Bahamas, Publ. 182, Carnegie Inst. of Washington, 1914, pp. 49–64. McClendon, J. F., On changes in the sea and their relations to organisms, Publ. 252, Carnegie Inst. of Washington, 1918, p. 258. Also Proc. Nat. Acad. Sci., 1917, p. 618.

[325] Kellerman, K. F., and Smith, N. R., Halophytic and lime precipitating bacteria, Science, vol. 41, 1915, p. 624.

to be below the number actually present. The optimum temperature of its activity was given as about 29.5°C., and it became totally inactive at 10°C., its greatest activity being hence in the warm and tropical waters and at shallow depths, Drew stating that below 350 fathoms it plays no part in the metabolism of the sea. Drew obtained a bacillus of similar character, but of less denitrifying activity, at a locality 70 miles west of Ushant Island, France.

Drew supposed the nitrates essential for the existence of the bacillus to be derived from the decomposition of organic matter in the sea, nitrates washed from the land, and perhaps from nitrogen-fixing bacteria. McClendon attempted the determination of the quantity of nitrates in the water at Tortugas and found with duplicate analyses that there was less than 0.01 mgm. of nitrogen per liter as ammonia and less than 0.01 mgm. per liter as nitrates and nitrites.[326] Raben found ten times these quantities in North Sea water. It may be that the activity of *Pseudomonas calcis* and perhaps other organisms had removed most of the nitrogen from the Tortugas waters.

Studies made by McClendon of the alkaline reserve of the waters at Tortugas as compared with waters elsewhere showed that the precipitation at Tortugas is not due to an excess of calcium in these waters, but to local conditions, and he raises the question as to whether the occasional high pH (8.35 during the day and 8.18 during the night (1917)) and hence low CO_2 content of the water may not be sufficient to explain the calcium carbonate precipitation, particularly if nuclei were present in the sea water to initiate

Bacterial activity not related to decay or organic matter has been said to make possible three different ways in which precipitation of calcium carbonate might occur.[328] 1. Nitrates in solution are reduced to nitrites which ultimately result in ammonia, this unites with carbon dioxide to form ammonium carbonate, which, reacting with the calcium sulphate in solution, forms calcium carbonate, and in waters saturated therewith this last is precipitated. 2. Ammonia may act directly on the bicarbonate to form the carbonate, as expressed in the following equation: $Ca(HCO_3)_2 + 2NH_4OH = CaCO_3 + (NH_4)_2CO_3 + 2H_2O$. 3. Bacteria use organic acids and the salts of these acids for food, and if any of these are organic salts of calcium, they may be broken up and the released calcium may unite with free carbon dioxide to form calcium carbonate.

[326] McClendon, J. F., On changes in the sea and their relations to organisms, Papers from the Dept. Marine Biology, Publ. 252, Carnegie Inst. of Washington, 1918, p. 252.

[327] McClendon, J. F., op. cit., pp. 254–255.

[328] Drew, G. H., op. cit.; Kellerman, K. F., and Smith, N. R., Bacterial precipitation of calcium carbonate, Jour. Washington Acad. Sci., vol. 4, 1914, pp. 400–402.

Drew concluded:

It can be stated with a fair degree of certainty that the very extensive, chalky mud flats forming the Great Bahama Bank and those which are found in places in the neighborhood of the Florida Keys are now being precipitated by the action of *Bacterium calcis* on the calcium salts in solution in the sea water. From this, the suggestion is obvious that *Bacterium calcis*, or other bacteria having a similar action, may have been an important factor in the formation of the various chalk strata in addition to the part played by the shells of Foraminifera and other organisms in the formation of rocks.[329]

The calcium carbonate precipitated is mainly, if not wholly, in the form of aragonite,[330] which is at first of a gelatinous character and later aggregates into spherulites.[331]

Lipman[332] attacked the conclusions of Drew and considered that there is no support for his explanation of the mechanism of $CaCO_3$ precipitation in natural sea waters,[333] and he reported the absence of nitrifying bacteria in open waters, although he found that "calcareous sand inoculation showed marked nitrite production."

Calcium-carbonate-depositing bacteria are said to have been found in mine waters of the Kimberly diamond region.[334] Lime carbonate covers iron pipes, stones, mine timbers, etc., and contains the following substances in the proportions given:

	Per cent
$CaCO_3$	82.56 to 89.50
$MgCO_3$	5.2 to 8.77
SiO_2	0.2 to 0.40
Al_2O_3, Fe_2O_3	0.14 to 2.80
Na_2SO_4	trace to 2.55
H_2O	0.90 to 3.92
Organic matter	1.56 to 2.66

The mine waters carry only 3.98 parts calcium oxide per million, 339.60 parts Na_2O per million, and 300.09 parts SO_3 per million. The slides of recently deposited material show an abundance of micrococci and bacilli, and the precipitation of the calcium carbonate was ascribed to these, as the

[329] Drew, G. H., op. cit., p. 41.

[330] Vaughan, T. W., The study of the earth sciences, etc., U. S. Naval Bull., vol. 18, 1923, p. 10.

[331] Vaughan, T. W., Dept. Marine Biology, Carnegie Inst. Washington, Publ. 182, 1914, p. 51; see also Johnston, J., Merwin, H. C., and Williamson, E. D., Am. Jour. Sci., vol. 41, 1916, p. 480.

[332] Lipman, C. B., Further studies on the Drew hypothesis of $CaCO_3$ precipitation in sea water, Year Book No. 21, Carnegie Inst. of Washington, 1922, p. 171.

[333] Lipman, C. B., Does nitrification occur in sea water?, Science, vol. 56, 1922, pp. 501–503.

[334] Parry, J., Minerals deposited by bacteria in mine water, Chem. News, vol. 125, 1922, pp. 225–228, 241–243, 257–259.

deposition was not due to evaporation and no agents other than the bacteria appeared to be operative.

A later article relating to precipitation of calcium carbonate by denitrifying bacteria is that of Merwin.[335] It is there stated that the work of denitrifying bacteria is essentially confined to the bottom, and that the number of *P. calcis* per cubic centimeter in the mud from off the east side of Andros Island is approximately 10,000 times as great as in the overlying surface waters. New samples of mud from the west side of Andros Island were studied by E. T. Erickson in order to ascertain the approximate quantity of organic matter in these muds which might serve as food for bacteria. A small quantity of such matter was found. The same sample was studied by K. F. Kellerman and N. R. Smith with respect to the bacteria, and they report as follows:

In the early work of the calcium precipitating organisms, the soluble salts of calcium, such as the acetate, malate, and succinate, were used. These were soon discarded not only because their presence in sea water is of little consequence but also on account of the utilization of the organic acid radical by some strains of bacteria with the resultant precipitate of the calcium from the saturated solution. In the latter work, most of which is still unpublished, calcium sulphate in a dializing sack is suspended in a sample of sea water.

A bacterial analysis of a sample of mud from the Bahama banks was made and found to contain on an average 565,000 bacteria per gram of the wet mud. Of these, approximately 15 per cent were of the *Ps. calcis* type and 70 per cent of the *Spirillæ* type, capable of producing strong ammonia from organic matter. Pure cultures of the *Ps. calcis* in sea water to which had been added 0.2 per cent peptone and 0.2 per cent potassium nitrate precipitate crystals and spheroids of calcium carbonate from the calcium sulfate. If only nitrate is added to the sea water, no growth takes place, a small amount of organic matter being necessary for the growth of the organisms. The *Spirillæ* produce strong ammonia from peptone but in pure culture do not precipitate calcium carbonate.

Since the mud from the Bahama banks contains a small quantity of organic matter, it was thought that a precipitate of calcium might be obtained by filling a dializing sack with mud and suspending it with a sack of calcium sulfate in sea water. While a few crystals were obtained, these were not very abundant. However, in the duplicate flask which had 2 grams of cooked egg albumin added to the mud, the results were striking. There was the usual heavy precipitate of calcium. These as well as numerous other experiments show the necessity for a supply of organic matter, with or without nitrates, for the metabolism of the bacteria and the precipitation of calcium carbonate.

Merwin's summary of calcium carbonate precipitation through the action of bacteria is as follows:

The precipitation of calcium carbonate in the sea is a very complex problem. Notwithstanding virtual unanimity that the surface layers of the ocean in tropical and sub-

[335] Merwin, H. E., Rept. Comm. Sedimentation, Nat. Research Council, 1923, pp. 35–57

tropical seas are saturated or supersaturated with reference to $CaCO_3$, positively established precipitation away from $CaCO_3$-secreting organisms is known in only a few places. There is a concatenation of inorganic and organic factors at those places, and at present it is not possible to evaluate the several factors concerned; but it appears that ammonifying bacteria, which include *Pseudomonas calcis*, may be among the agencies responsible for the precipitation where it is known.

Later work on denitrifying bacteria by Smith[336] states that bottom muds composed very largely of chemically precipitated material contain bacteria which will precipitate $CaCO_3$, and that sufficient nutrient material is present to support them. It is suggested that ammonifying bacteria (*Vibrio*) are probably more important in the precipitation than denitrifying forms (*Pseudomonas*).

Lipman's[337] latest paper gives conclusions to the effect that all the bacteria studied by him have the ability to precipitate calcium carbonate from certain media, but that "when tested in sea water alone, none of them, not even Drew's *Pseudomonas*, possesses that power. The conclusion seems irresistible, therefore, that if lime precipitation from sea-water is accomplished by bacteria under natural conditions, proof therefor is wanting."

Smith's[338] final statement is to the effect that the bacteria in sea-bottom muds and sea water may be placed in six main groups according to their physiological activities, that the denitrifiers and strong ammonifiers dominate in the muds whereas weak ammonifiers dominate in the sea water, and that "calcite is formed from calcium sulphate as the result of growth of bacteria; the more plentiful the food, the better is the chance for the formation of calcite," and that "bottom mud provides a nutrient for production of a small amount of calcite."

The latest contributions to the work of bacteria in the precipitation of calcium carbonate are those of Bavendamm[339] and Field.[340] Bavendamm states that relatively few bacteria occur in the white calcium carbonate muds of the Andros Banks and off the west coast of Andros, but that on the coast of Williams Island and especially in the mangrove swamps situated further inland the number of bacteria may be large, the surface layers of the mangrove swamp of Williams Island, for example, containing over 16,000,000

[336] Smith, N. R., in Vaughan, T. W., Oceanography and its relations to other earth sciences, Jour. Wash. Acad. Sci., vol. 14, 1924, pp. 323–325.

[337] Lipman, C. B., op. cit., pp. 181–191.

[338] Smith, N. R., Report on a bacteriological examination of "chalky mud" and sea-water from the Bahama Banks, Publ. 344, Carnegie Inst. Washington, 1926, pp. 67–72.

[339] Bavendamm, W., The possible rôle of micro-organisms in the precipitation of calcium carbonate in tropical seas, Science, vol. 73, 1931, pp. 597–598.

[340] Field, R. M., Geology of the Bahamas, Abstract, Bull. Geol. Soc. Am., vol. 42, 1931, pp. 193–194; Microbiology and the marine limestones, Abstract, Geol. Soc. Am., Preliminary list of titles and abstracts, 1931, pp. 14–15.

per gram, and at a depth of 4 feet over 2,000,000 per gram. Bavendamm "believes that the bacterological process of calcium carbonate precipitation may be confined to certain localities" and it is assumed "that mangrove swamps or similar places represent the natural localities for the micro-biological calcium carbonate precipitation," the conditions being those of fresh or brackish water as there is stated to be a small bacterial population in the open sea. Field states that marine bacteria are probably negligible in the precipitation of calcium carbonate and that all bacteria are relatively more important in the muds and fresh and brackish waters of Andros Island than in the marine muds covering the banks. He further states that the bulk of the calcium carbonate mud on the Bahama Banks has been derived from the west coast of Andros Island and that there is no direct evidence that the carbonate muds of Andros Island or the muds on the banks are of marine origin, the former seeming rather to be of fresh or brackish water origin since they contain organisms only of those environments; and (1931, 2) that "such bacteria as *Bacterium calcis*, or *Pseudomonus calciphila* and *P. calcipræcipitans* do not exist, but that forms such as the sulphate-reducing bacteria, ammonifying bacteria, denitrifying bacteria and the agar-liquefying bacteria are important but indirect agents in the precipitation of calcium carbonate." He gives the five following reactions as those in which the bacteria appear to play a fundamental rôle.

$$(NH_4)_2CO_3 + CaSO_4 = CaCO_3 + (NH_4)_2SO_4$$
$$RS + CO_2 + H_2O = H_2S + RCO_3$$
$$Ca(HCO_3)_2 + 2NH_4OH = CaCO_3 + (NH_4)_2CO_3 + 2H_2O$$
$$Ca(COOCH_3)_2 + O_2 = CaCO_3 + 3H_2O + 3C$$
$$Ca(HCO_3)_2 \rightleftarrows CaCO_3 + H_2O + CO_2$$

The foregoing indicates that direct precipitation of calcium carbonate through the action of bacteria may not take place. However, further research is desirable.

Putrefaction of organic matter under some conditions produces ammonia. Excellent illustrations frequently occur in the tobacco country of Kentucky where the seed beds are fertilized and watered several times in spring with a mixture of water and chicken manure. The manure is prepared for mixing with water by placing it in covered barrels or boxes after first having been slightly moistened. If permitted to remain in the barrels or boxes for too long a time, the production of ammonia may become so great as to be easily perceptible at distances of 25 or more feet. Ammonia so produced in water may combine with carbon dioxide, producing ammonium carbonate, which, reacting with calcium salts in solution, converts the calcium to the carbonate, which in saturated waters is precipitated. Experiments by

Murray and Irvine[341] and by Irvine and Woodhead[342] have shown that sea water in which organic matter decays has all its calcium salts changed to carbonates and precipitated to the extent possible. The equations which have been postulated to represent these reactions are as follows:

$$CaSO_4 + (NH_4)_2CO_3 = CaCO_3 + (NH_4)_2SO_4$$
$$CaCl_2 + (NH_4)_2CO_3 = CaCO_3 + 2NH_4Cl$$

The putrefaction is largely and perhaps wholly due to decay-producing bacteria, and to certain forms (*Vibrio*) is to be mainly referred the production of the ammonia.[343] The precipitated calcium carbonate is not known to be different from that which has been thought to be precipitated by denitrifying or other bacteria. According to Gee,[344] the precipitation of calcium carbonate by ammonia requires a pH which has not been recorded under natural conditions.

Magnesium is also precipitated, but the precipitation is much slower and takes place after most, if not all, of the calcium has gone out of solution.[345, 346] In one of the experiments of Murray and Irvine,[347] a mixture of urine and sea water, after standing several days, gave the precipitate noted under A. The liquid was filtered and permitted to stand ten days longer, when the precipitate under B was obtained.

	A *Per cent*	B *Per cent*
Water and organic matter (containing 7.38 per cent ammonia in A)	31.81	20.25
$CaCO_3$	4.85	75.35
Phosphate of magnesia and ammonia	51.10	
Phosphate of lime	12.24	
$MgCO_3$		1.02
Phosphate of magnesia		3.38
	100.00	100.00

Carbon dioxide is also a product of organic decay and where such decay is large, the tendency would be to retain in solution any calcium carbonate precipitated through reaction of calcium sulphate with ammonium carbonate.

[341] Murray, J., and Irvine, R., On coral reefs and other carbonate of lime formations in modern seas, Proc. Roy. Soc. Edinburgh, vol. 17, 1891, pp. 79–109.

[342] Irvine, R., and Woodhead, G. S., On the secretion of carbonate of lime by animals, Proc. Royal Soc. Edinburgh, vol. 15, pp. 308–320, 1889; vol. 16, pp. 324–354, 1890.

[343] Smith, N. R., in Vaughan, T. W., op. cit., p. 325.

[344] Gee, H., Rept. Comm. Sedimentation, Nat. Research Council, 1931, p. 13.

[345] Daly, R. A., The limeless ocean of pre-Cambrian time, Am. Jour. Sci., vol. 23, 1907, p. 104.

[346] Daly, R. A., First calcareous fossils and the evolution of limestone, Bull. Geol. Soc. Am., vol. 20, 1909, p. 163.

[347] Murray and Irvine, op. cit., p. 104.

According to Linck, the calcium carbonate precipitated through reaction of calcium sulphate with ammonium carbonate is in the form of aragonite.[348] This statement may require some revision.[349]

The quantity of calcium carbonate precipitated through ammonium carbonate may be very large, but existing data do not permit an estimate to be made of the part it takes or has taken in the formation of limestones. The finely divided condition renders it particularly adapted to play an important rôle in the chemical reactions of the bottom deposits of which it becomes a part.[350]

(B) LIMESTONES OF CHEMICALLY INORGANIC ORIGIN. The limestones which owe their origin to chemical conditions of inorganic character are not readily differentiable from those owing their origin to other causes and it is probable that some parts of many, and perhaps most limestones, should be referred to a chemically inorganic origin.

(B_1) *Limestones Resulting from Change of Conditions.* As noted above, the quantity of calcium carbonate held in solution is largely dependent upon the quantity of carbon dioxide in the water. This quantity in turn is almost wholly determined by the carbon dioxide in the air above the water and by the temperature, and in comparison with these two factors all others are subsidiary.[351] The effects of variations in the carbon dioxide content of the air upon the carbon dioxide content of the water and the solubility of calcium carbonate are shown in table 53.[352]

Table 54 shows the relation of the solubility of calcite to temperature, to which the quantity of carbon dioxide in water is more or less inversely related, rising and falling with fall and rise of temperature.[353]

In spite of the fact that the calcium carbonate in ocean waters is small,

[348] Linck, G., Die Bildung der Oolithe und Rogensteine, Neues Jahrb. f. Min., Beil. Bd. 16, 1903, p. 500.

[349] Johnston, J., Merwin, H. E., and Williamson, E. D., The several forms of calcium carbonate, Am. Jour. Sci., vol. 41, 1916, p. 480.

[350] Field has proposed the name *drewite* for the fine calcareous oozes which occur about some parts of the West Indies region, the name being given in honor of Doctor G. H. Drew, who developed the view of precipitation of calcium carbonate by denitrifying bacteria. Field, R. M., Investigations regarding the calcium carbonate oozes at Tortugas, and the beach-rock at Loggerhead Key, Yearbook 18, Carnegie Inst. Washington, 1919, pp. 197–198. The name *vaughanite* has been proposed for the fine-textured limestones which are supposed to represent indurated drewite. Kindle, E. M., Nomenclature and genetic relations of certain calcareous rocks. Pan-Am. Geol., vol. 39, 1924, pp. 369–370. The writer sees little use for either of these names.

[351] Johnston, J., and Williamson, E. D., The rôle of inorganic agencies in the deposition of calcium carbonate, Jour. Geol., vol. 24, 1916, p. 738.

[352] Johnston, J., and Williamson, E. D., op. cit., p. 732.

[353] Wells, R. C., The solubility of calcite in water in contact with the atmosphere and its variation with temperature, Jour. Washington Acad. Sci., vol. 5, 1915, p. 617; Johnston, J., and Williamson, E. D., op. cit., p. 733.

the ocean appears to be virtually saturated therewith. Murray expresses the view[354] that "the ocean as a whole remains just about saturated for calcium carbonate," a view supported by the studies of Thoulet,[355] the experiments of Mayor,[356] and observations of Vaughan[357] and others on the lagoons and bays adjacent to the coral reefs of the Atlantic and Pacific oceans; and Johnston and Williamson express the opinion that the "surface layers of the ocean, except in the polar regions and within currents of cold water—in other words, the warmer portions of the ocean water—are substantially saturated with $CaCO_3$."[358] McClendon found that all sea water is supersaturated with $CaCO_3$, and that the latter will be precipitated if the water is shaken with calcite or aragonite crystals.[359] The same con-

TABLE 53

CO_2 in the atmosphere expressed:		Free CO_2 of H_2CO_3 in solution, parts per million	Solubility of calcite, parts $CaCO_3$ per million
As partial pressure	As parts per 10,000 by volume		
0.0001	1.0	0.18	44
0.0002	2.0	0.36	55
0.00025	2.5	0.45	59
0.0003	3.0	0.55	63
0.00035	3.5	0.64	66
0.0004	4.0	0.73	69
0.0005	5.0	0.90	75

TABLE 54

Temperature, centigrade	Solubility of calcite, parts $CaCO_3$ per million
0	81
5	75
10	70
15	65
20	60
25	56
30	52

[354] Murray, J., and Hjort, J., Depths of the ocean, 1912, p. 180.

[355] Thoulet, J., Étude bathylithologique des côtes du Golfe de Lyons, Ann. de l'Institut Océanographique, IV, fasc. 7, 1912, pp. 32–35.

[356] Mayor, A. G., Submarine solution of limestone, Proc. Nat. Acad. Sci., vol. 2, 1916, pp. 28–30.

[357] Vaughan, T. W., The present status of the investigations of the origin of barrier coral reefs, Am. Jour. Sci., vol. 41, 1916, p. 133.

[358] Johnston, J., and Williamson, E. D., op. cit., p. 735.

[359] McClendon, J. F., On changes in the sea and their relations to organisms, Publ. 252, Carnegie Inst. of Washington, 1918, pp. 215 and 257.

clusion was reached by Wells, who states that "sea water appears to be so far saturated with calcium carbonate that in contact with the atmosphere at 1°C. it neither has nor acquires an appreciable solvent action on calcite."[360]

Under conditions of saturation, calcium carbonate is precipitated following escape of carbon dioxide from the water. This is favored or caused by passage, over such water bodies, of currents of atmosphere having a carbon dioxide content below that required to maintain equilibrium with the carbon dioxide content of the water; by agitation of the water, facilitating escape of carbon dioxide; by rise of temperature; and by less important causes. The variation in carbon dioxide content in the atmosphere over a body of water at the present time is roughly about one-third or one-fourth of the whole, and during geologic time the variations may have been of greater magnitude.[361] According to Johnston and Williamson,[362] if the air in actual contact with a solution varies in the carbon dioxide content from 3.3 to 3 parts per 10,000, the solubility is decreased from 65 to 63 parts per million and the two parts are thrown out of solution and precipitated, providing supersaturation does not take place. The precipitation of an equal quantity of calcium carbonate occurs with a rise of temperature of 2°C. Due to the wide range in the surface temperatures of the ocean, the low temperatures over the bottom of the ocean, and the presence of currents in the waters, it naturally follows that waters over extensive areas have considerable range in their capacity to retain calcium carbonate in solution. At the polar regions the waters sink and flow southward toward the equatorial regions. On their way thereto, they probably receive additions of carbon dioxide from decaying organic matter and become charged to the limits possible, and shells of surface plankton sink into them and undergo more or less solution. The pressure at these depths appears to have no direct influence on the water's solvent ability, although it possibly permits a greater retention of carbon dioxide, thus indirectly increasing solution. This water reaches the equatorial regions and slowly rises; carbon dioxide is lost to the atmosphere due to rising temperature and perhaps also to the fact that the partial pressure of the carbon dioxide of the atmosphere is inadequate to maintain an equilibrium with the carbon dioxide in the water. Ultimately the quantity of calcium carbonate in solution may reach saturation, and precipitation occurs, and such very probably is now taking place in tropical and subtropical regions. It also is probably occurring where deep waters are compelled to flow over shallow bottoms, such as some of the

[360] Wells, R. C., New determinations of carbon dioxide in the water of the Gulf of Mexico, Prof. Paper 120, U. S. Geol. Surv., 1918, p. 9.

[361] McClendon, J. F., op. cit., p. 216. Tables showing variations in the CO_2 content of the air.

[362] Johnston, J., and Williamson, E. D., op. cit., p. 738.

banks of the West and East Indies, as exemplified by that on the west side of Andros Island of the former. The same result is produced where vertical currents or upwellings, which are known to occur on some coasts, bring the deeper cold waters to the surface.[363] As exemplifying the quantitative effects of change of temperature in the precipitation of calcium carbonate, Johnston and Williamson give the following: A current of sea water of temperature of 15°C. is assumed to become saturated with calcium carbonate, and after traveling 600 miles at a rate of about 16 miles per day, to attain a temperature of 20°C. This rate of travel would permit new water to be brought completely over the 600 miles ten times each year.

On being warmed from 15 to 20°C., the water would precipitate 5.4 parts calcium carbonate per million by weight or 2 parts per million by volume. If this calcium carbonate settled to the bottom, it would make an annual deposit over the entire area of two one-millionths of the depth of the current. For a current 100 feet deep the annual deposit over the entire area would be 2 mm. annually, or one foot in 300 years. The assumption that the deposition would take place uniformly over the entire area is probably not one that would be realized, as the rise in temperature would not be uniform, the currents would transport the precipitate to some places more extensively than others, and if the current were underlain by colder waters with small calcium carbonate content, some of the precipitate would again go into solution. The effects would be more apparent where the warming of waters occurred over shallow bottoms.

Submarine volcanic action would heat and agitate adjacent waters, thus driving out carbon dioxide and compelling carbonate precipitation. This problem has been theoretically studied by Kania,[364] who concludes that a lava flow 20 square miles in area and 100 feet thick issuing at a temperature of 900°C. and accompanied by the usual gas emissions is capable of precipitating a mass of limestone equal to 191 circular lenses, each 500 feet in diameter and 50 feet thick. A similar submarine vent intermittently giving off gases during a period of a million years, thus heating and agitating the sea water with expulsion of carbon dioxide therefrom during that time, would lead to the precipitation of a mass of limestone 1000 feet thick, extending over an area of 7,000 square miles. It is probable that the figures given in this paragraph should not be taken too seriously, but it seems probable that some carbonate deposition may be due to submarine volcanic action and that in this way may be explained unfossiliferous limestones which occur interbedded with subaqueous lava flows.

[363] McClendon, J. F., op. cit., p. 215.

[364] Kania, J. E. A., Precipitation of limestone by submarine vents, fumaroles, and lava flows, Am. Jour. Sci., vol. 18, 1929, pp. 347–359.

Waters issuing from the ground as springs may experience release of pressure, fall of temperature, and agitation. Such waters may be high in carbon dioxide and calcium carbonate, and the escape of the carbon dioxide on reaching the surface would permit precipitation of the carbonate. Thus is formed the tufa about many hot and cold springs. Streams which are carrying large quantities of calcium carbonate precipitate some of it at falls and rapids because agitation permits escape of some of the carbon dioxide. In this way developed the travertine of the Tivoli River of Italy[365] and similar deposits elsewhere.

The Catinga limestone of Bahia, Brazil, seems to have formed largely as a consequence of loss of carbon dioxide by the depositing waters.[366] The calcium carbonate was dissolved from older limestones of the region and deposited where the waters were agitated, evaporated, or lost carbon dioxide through rise of temperature. The thickness of the limestone ranges up to 100 feet. The deposition began in the Tertiary and is still continuing. It usually occurs where the water is agitated, and "Any downstream slope of the stream bed that causes a rippling of the water exposes it to the air, liberates more carbon dioxide, and thus causes an increased deposition of lime on the downstream side." This builds up deposits which form barriers ranging in height up to 4 meters. These change the places of agitated waters and the places of deposition.

> Where a broad, gentle, and rather even slope carries the lime charged waters in shallow sheets toward a channel, the lime is precipitated more rapidly along the edge of the plain, where, on account of a change to a steeper grade, the water breaks into ripples or spray. This causes the bluff to encroach steadily on the low ground, and the process must eventually lead to the low ground being entirely filled up.

These bluffs overhang at the top and are full of caverns which contain stalactites. The overhanging portions break off and form talus at the base, which becomes covered by later deposits. Some of the limestone bluffs are 75 to 90 feet high. The case is remarkable in that it is an example of extensive limestone of decided thickness forming on land.

Much tufa is associated with waterfalls,[367] and in numerous places these have had heights increased by tufa formation, as near Covington, Virginia. In some instances tufa or travertine formations have dammed small streams.

There are many ancient limestones of striking uniformity of grain which contain no fossils. Such are the magnesian limestones and dolomites of

[365] Cohn, F., Über die Entstehung des Travertin in den Wasserfällen von Tivoli, Neues Jahrb. f. Min. etc., 1864, pp. 580–640.

[366] Branner, J. C., Aggraded limestone plain of the interior of Bahia, etc., Bull. Geol. Soc. Am., vol. 22, 1911, pp. 187–206.

[367] Gregory, J. W., Constructive waterfalls, Scottish Geog. Mag., vol. 27, 1911, p. 537.

the Belt terrane, the Siyeh and Sheppard limestones of northwestern Montana, limestones described by Daly[368] along the International Boundary, the Knox dolomite, and others. Perhaps these limestones in the cases where they are dolomitized had their fossils destroyed in the process. This explanation, however, will not apply to strata which are still composed of little recrystallized calcium carbonate. Moreover, most limestones are composed of fossils only in part, and that usually the minor part, the remaining portion consisting of finely divided calcite, much of which has few traces of organic matter. This was found to be true for the richly fossiliferous Anticosti and Cincinnati sections and has been demonstrated in other very fossiliferous limestones. It is possible that this finely divided calcium carbonate was at least partly produced by bacterial action, reaction of calcium sulphate with ammonium carbonate resulting from organic activity or decay of organic matter, or escape of carbon dioxide.

(B_2) *Limestones Due to Evaporation.* Under this heading are considered those limestones which develop under conditions in which evaporation is the important factor, although the deposition may not entirely be due to this cause. The deposition occurs in caves, about springs, in streams, in lakes and playas, and in arms of the sea.

The deposits in caves form the characteristic stalactites, stalagmites, and kindred structures. They have a more or less concentrically banded structure parallel to the elongation, this being particularly true with respect to the stalactites. Colors are various, depending upon the impurities which are deposited with the calcite. Caves are known to have been completely filled with calcium carbonate deposits of this origin.[369]

The deposits about springs are known as tufa, sinter, or travertine, the tufa and sinter being very porous and the travertine compact and banded. The deposits are mostly made about hot springs, and evaporation is probably of minor importance in their development, the escape of carbon dioxide and organic activity being the factors to which most of the deposition is due. The springs of the Yellowstone National Park contain algæ which are held to be important in deposition.

Probably the most important spring deposits in the United States are those of Yellowstone National Park, but they are common about many springs, particularly those of limestone regions. Analyses of tufa from a spring of the Park and from a spring in Utah are given below.

The rate of deposition of spring deposits is often very rapid. At the

[368] Daly, R. A., First calcareous fossils and the evolution of limestone, Bull. Geol. Soc. Am., vol. 20, 1909, pp. 167–168.

[369] Allison, V. C., The growth of stalagmites and stalactites, Jour. Geol., vol. 31, 1923, pp. 105–125.

baths of San Vignone in Tuscany the travertine is deposited at the rate of 6 inches per year and at San Filippo, Sicily, a foot in four months.[370]

Some of the onyx marbles are spring deposits. They occur as beds interbedded with tuffs and breccias and as irregular masses in clays and other sediments.[371] In the province of Oran, Algeria, is a deposit which has an estimated area of 12 acres. This is large. The common association of onyx with volcanic deposits suggests that the waters which were responsible for the deposition of this calcium carbonate were connected with volcanic activity.

TABLE 55

	1*	2
SiO_2	0.09	8.40
Al_2O_3, Fe_2O_3	0.11	1.31
CaO	55.37	46.38
MgO	0.35	3.54
K_2O	0.04	0.22
Na_2O		0.48
Li_2O		Trace
NaCl	0.10	
SO_3	0.44	
CO_3	43.11	38.20
P_2O_5		Trace
H_2O	0.32	1.71
C, organic	0.17	
	100.10	100.24

* 1. Travertine, Mammoth Hot Springs of the Yellowstone Park, F. A. Gooch, analyst, Bull. 229, U. S. Geol. Surv., p. 323.

2. Main terrace, Redding Spring, Great Salt Lake desert, by R. W. Woodward, Rept. U. S. Geol. Surv., Explor. 40th Par., 1878, p. 502.

There is great variation in the composition of the calcium carbonate deposit of springs, as is shown by the two analyses in table 55. Magnesian carbonate is almost always present with the calcium.

Some tufa has been ascribed to deposition by moss, as stated by Macfayden[372] for a mountain stream of Switzerland, the waters being of low

[370] Lyell, C., Principles of geology, 11th ed., 1875, p. 402.

[371] Merrill, G. P., The onyx marbles, etc., Annual Rept. Smithsonian Inst. for 1893, 1895, pp. 541–585.

[372] Macfayden, W. A., On the deposition of calcareous tufa in a mountain stream, Geol. Mag., vol. 65, 1928, pp. 1–5.

calcium carbonate content. La Touche[373] has made the same explanation for tufa in Burma.

In the development of the tufas of salt lakes and playas it is possible that evaporation is the dominant process involved, although it seems likely that algal activity plays a more important rôle. What are probably the most extensive lake tufas in the United States, if not in the world, are those of the Lahontan basin. Three varieties have been distinguished which have been designated lithoid, thinolitic, and dendritic. The lithoid tufa is the oldest and hence underlies the others, although some dendritic tufa is interbedded with it. This tufa is either compact and essentially pure calcium carbonate or it serves as a cement for gravels. Its color is gray, and it occasionally contains shells of gastropods. It occurs as beds and dome-shaped masses with banded structure and not infrequently constitutes the cores of other tufa masses. The thinolitic tufa, second in order of deposition, is composed of orthorhombic prisms 6 to 8 inches long and about half an inch thick These prisms have generally been supposed to be replacements of some other mineral, which King suggested may have been gaylussite, but Dana showed that this could not have been the case. The thinolitic tufa has a banded structure, and near its outer limit it is interbedded with dendritic tufa. It has a thickness of around 6 to 8 feet, but near Pyramid Lake it is 10 to 12 feet thick. The dendritic tufa usually occurs in spheroidal and mushroom, or dome-shaped, masses with concentric arrangement and an internal dendritic structure. There are areas of several square miles which are completely covered with domes of this type of tufa with the diameters of the domes up to 5 and 6 feet. These structures seem best interpretable as of algal origin and not due to evaporation.

Some of the tufa masses are large and form crags, castle-like structures, towers, shafts, etc., and in Pyramid Lake is an island formed wholly of tufa. Some of the towers and shafts of tufa are 50 to 60 feet high. The large masses have a central portion of compact lithoid tufa. This is surrounded by a band of thinolitic tufa, and over the outside and constituting the major portion is a covering of dendritic tufa. The maximum thickness of the tufa is 50 to 60 feet, but 20 feet is an average maximum.[374]

Table 56 shows the composition of the three varieties of Lahontan tufa.

According to Grabau,[375] the Permian magnesian limestone of Durham, England, has the appearance of being a tufa deposit of the Lahontan type,

[373] La Touche, T. H. D., Geology of the northern Shan States, Mem. Geol. Surv. India, vol. 39, pt. ii, 1913, pp. 326–327.

[374] Russell, I. C., Geological history of Lake Lahontan, Mon. 11, U. S. Geol. Surv., 1885, pp. 189–222.

[375] Grabau, A. W., Principles of stratigraphy, 1913, p. 341.

as many of the beds are composed of spherical masses of dolomite which resemble those of the Lahontan region. These, too, are most probably of algal origin.

The tepetate of the semi-arid Southwest consists of lime deposits made over the flood plains and alluvial fans and cones of the ephemeral, but often torrential, rivers. The lime is dissolved from limestones near the heads of the streams, and after deposition it either forms a crust over the surface or serves as a cement for clastic materials. Another lime deposit of the semi-arid Southwest is that known as caliche, which in parts of west Texas, and no doubt elsewhere, is so compact as to be used for road surfacing, and locally forms deposits of several feet thickness on and just beneath the surface, these conforming to the surface in the manner of a bed and simulating structures so excellently as to have been in a few cases used for detailing by those unfamiliar with such deposits.[376]

TABLE 56

	LITHOID TUFA	THINOLITIC TUFA	DENDRITIC TUFA
Insoluble	1.70	3.88	5.06
CaO	50.48	50.45	49.14
MgO	2.88	1.37	1.99
Al_2O_3, Fe_2O_3	0.25	0.71	1.29
CO_2	41.85	40.90	40.31
H_2O	2.07	1.50	2.01
P_2O_5	0.30	Trace	Trace
Cl. Sulphuric acid	Trace	Trace	Trace
	99.53	98.81	99.80

Fresh waters flowing into bodies of salt water spread over the surface of the latter, and for a time the fresh and salt waters are to some degree separate. This permits evaporation of the former and also escape of carbon dioxide. Precipitation of calcium carbonate may take place as a consequence. Rivers flowing toward the equator, as the Rhone and Mississippi, may have a part of their calcium carbonate thus precipitated.

The mingling of fresh waters carrying calcium carbonate in solution with salt waters of high salinity leads to the precipitation of the carbonates. Thus, tributaries of Great Salt Lake carry much calcium carbonate in solution, but the lake itself contains little.[377] The Dead Sea has attained a

[376] Breazeale, J. F., and Smith, H. V., Caliche in Arizona, Bull. 131, Univ. Arizona Experiment Station, 1930, pp. 419–441; Lonsdale, J. T., The occurrence of caliche in Arizona, Proc. Oklahoma Acad. Sci., vol. 5, 1925, pp. 132–136.

[377] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 156–159, 169–171.

degree of concentration so high that many of the sodium compounds have been precipitated, and at their entrance into the Dead Sea the waters of the Jordan precipitate their carbonates and also their calcium sulphate. High concentration of the waters of the two basins is the cause, the deposits thus being related to evaporation and being localized about the mouths of streams tributary to the saline basins. (For further consideration of this phase of limestone deposition, consult the subject of Gypsum, Rock Salt, and other Saline Residues.)

(C) LIMESTONES OF MECHANICAL ORIGIN. The deposition of a great deal of the shell limestone is as truly mechanical as that of gravels and quartz sands, and the deposits are really sands and gravels of shell matter. After such organic matter is thrown on a beach, it may be picked up by wind and transported inland to be deposited in dunes. Thus, there are dunes on Bermuda composed entirely of coral fragments, shell fragments, and shells of foraminifera. An older similar lime deposit of Bermuda now consolidated is known as a sandstone, although nearly pure calcium carbonate. On the shores of the Arabian Sea is a limestone of eolian deposition known as the Miliolitic formation because of the abundance of shells of *Miliola*.[378] The Junagarh limestone overlying the Deccan trap in the Kathiawar district of western India is also ascribed to this origin. In Ireland are dune sands on the coast of Galway which are composed very largely of the shells of foraminifera.[379] The products are of marine production, but eolian deposition.

There are also calcium and calcium-magnesium carbonate deposits which have resulted from both mechanical deposition and production. Arid regions occasionally have calcareous sands, and they are extremely common on sea beaches whose shores are composed of limestones. Many sands on the beaches of Anticosti Island and Gotland have over 90 per cent of the grains composed of particles worn from the limestone shores, and in many instances they contain remnants of fossils from these rocks. The sands of some streams are also composed very largely of calcium carbonate. Mechanically transported and deposited calcium carbonate must have formed limestones in the past, and the ripple-marked and cross-laminated limestones so common in many geological sections plainly indicate calcium carbonate sediments of mechanical deposition. Calcium carbonate oolites are commonly cross-laminated, and at the time of deposition with such structures were as truly sands as if they had been composed of quartz.

[378] Evans, J. W., Mechanically-formed limestones from Junagarh (Kathiawar) and other localities, Quart. Jour. Geol. Soc., vol. 56, 1900, pp. 559–583; Chapman, F., Notes on the consolidated eolian sands of Kathiawar, Quart. Jour. Geol. Soc., vol. 56, 1900, pp. 584–588.

[379] Grabau, A. W., Principles of stratigraphy, 1913, pp. 573–577.

Limestones mechanically formed should have most of the physical characteristics of sediments thus made. Excellent sphericity is not favored for those calcium carbonate particles which have the calcite cleavage well developed, but where such is not the case, there are no reasons why sphericity should not be present to the degree found on other particles.

There appears to be considerable finely divided calcium carbonate carried in suspension, and some of this may be of colloidal dimensions. The deposition of this material apart from calcium carbonate of other derivation would lead to fine-grained limestone.

Limestones of mechanical origin, unless subsequently cemented so as to close original pore space, would have porosity and permeability commensurate with sizing, sorting, and packing of the composing particles, and there seem to be no good reasons why the porosity may not be as high as in other sediments of mechanical origin. Limestone sands are described as common associates of existing coral reefs, and such probably was the case in the ancient reefs, with which also oolites are not uncommonly associated. This permits the postulate that limestones with original porosity should be present on the margins of ancient reef formations. Also, in this connection, it may be noted that reef rocks should have considerable original porosity, as many of the forming organisms periodically seal up empty spaces of abandoned skeletal matter. Howard[380] seems to lean to the view that most limestone porosity is secondary and owes its origin to erosion preceding deposition of the overlying material. This view may be correct, but reef limestones and limestones whose composing materials were mechanically deposited cannot fail to have original porosity.

Summary

It is obvious that any limestone may have had various processes contribute to its formation, and it is probable that two or more of these have functioned in the formation of every limestone. A determination of the contributions of the various processes is not possible, except for that fraction derived from shell and similar matter, and in this case only the minimum is determinable, as an unknown quantity has been ground to an unrecognizable condition in the intestinal tracts of organisms. The limestone "paste" separating shell matter may have originated in several ways. Before a complete visualization of the environment of deposition of most ancient limestones is possible, determinations of the contributions by the different methods of calcium carbonate precipitation must be approximated.

It must also be appreciated that limestones may develop in environments

[380] Howard. W. V., A classification of limestone reservoirs, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 1153–1161, and Bull. Am. Pet. Inst., vol. 10, 1929, pp. 14–15.

whose extremes are the dunes of arid regions and the still waters of the deep sea, that calcium carbonate particles may be produced and deposited in the same environment, or they may be produced in one environment and be deposited in another. Thus, particles of marine production may attain deposition in seashore dunes. It follows that caution in interpretation is a virtue, lest it be concluded that the environment of production is also that of deposition.

DOLOMITES (DOLOMITE LIMESTONES)[381]

Dolomites, or dolomite limestones, are dominantly composed of the double carbonate of calcium and magnesium as a distinct compound, the ratio of the calcium to the magnesium carbonate being 54.35 to 45.65. Doubt has been expressed as to whether dolomite is a solid solution or a compound,[382] but the work of both Mitchell, and Wyckoff and Merwin,[383] particularly the latter, has shown that it "is a chemical compound distinct from calcite and magnesite." In many cases the magnesium of dolomite is replaced by manganese and ferrous iron, both of which may enter the mineral without changing its properties.

There seem to be all gradations between limestones composed entirely of calcite and those entirely composed of dolomite, but analyses show that limestones do not seem to be common in which the dolomite-calcite ratios are between 80:20 and 20:80, most limestones seeming to be either dominantly dolomite or dominantly calcite.[384] Attempts have been made to determine a percentage of magnesium carbonate which might serve as a boundary between calcite and dolomite limestones,[385] but nothing satisfactory has been accomplished. Perfectly pure dolomite limestones seem to be rare. Calcium is commonly in excess in most dolomites, but in rare cases magnesium exceeds the quantity required for normal dolomite, this excess then existing either in solid solution in the dolomite, isomorphous therewith, or as free crystals of magnesite. Most excess calcium probably is

[381] For detailed consideration of the dolomite problem, the monograph by F. M. Van Tuyl, The origin of dolomite, Iowa Geol. Surv., vol. 25, 1914, pp. 241–422, should be consulted. Manuscripts prepared by Professors Van Tuyl and E. Steidtmann were used by the writer in preparing the manuscript on dolomite for the first edition of this book. With slight changes the outline of Van Tuyl on the occurrence of dolomite has been followed.

[382] Mitchell, A. E., Studies on the dolomite system, Jour. Chem. Soc., vol. 123, 1923, pp. 1052–1069, 1087–1094.

[383] Wyckoff, R. W. G., and Merwin, H. E., The crystal structure of dolomite, Am. Jour. Sci., vol. 8, 1924, pp. 448–461.

[384] Steidtmann, E., Origin of limestones as disclosed by stains and other methods, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 431–450.

[385] Forchhammer, G., Jour. Prakt. Chemie, vol. 49, 1850, p. 52; Pfaff, F. W., Neues Jahrb., Beil.-Bd. 23, 1907, p. 529.

in the form of free crystals of calcite, but some may be in solid solution in the dolomite or isomorphous therewith; the quantity present not as free crystals may reach as much as 20 per cent.[386] The quantity of magnesium carbonate isomorphous in dolomite seems to be small. Limestones which do not contain the double carbonate of calcium and magnesium in sufficient quantity to be termed dolomites may be designated dolomitic limestones.

Dolomite and calcite limestones usually are readily differentiable by means of Lemberg's solution[387] and also by treatment with cold hydrochloric acid.[388] Calcite turns blue on treatment with the Lemberg solution, whereas dolomite does not change color.

Many dolomites and dolomitic limestones become yellow or brownish on exposure, the fresh rock being of lighter color. This change of color arises from oxidation of ferrous iron compounds, probably in most cases ferrous sulphide or ferrous carbonate, and some ferrous iron may replace magnesium in the double carbonate. This change of color, however, is not peculiar to dolomites or dolomitic limestones, as ferrous iron compounds in the form of carbonates and sulphides occur equally abundantly in many calcite limestones as well as in other rocks.

Textures of dolomites range from very fine-grained to medium- and even coarse-grained, the last not common except in some of those which have experienced anamorphism. Some dolomites are very compact; others are extremely porous or cavernous. The pores or small cavities are supposed in some instances to be due to solution of calcareous fossils and particles of calcite, or to shrinkage attending dolomitization of calcitic limestones, this transformation being attended by a decrease in volume of 12.1 per cent. Other factors than the two mentioned may also lead to the occurrence of pore space, as, for instance, primary deposition of detrital or other particles of dolomite.

Many dolomites have a brecciated appearance and many contain fragments of pre-existing rocks. A Permian dolomite of Texas carries fragments of lignite. These are interpreted as representing pieces of wood that floated

[386] Foote, H. W., and Bradley, W. M., The isomorphism between calcite and dolomite, Am. Jour. Sci., vol. 37, 1914, p. 339. Ford, W. E., Studies of the calcite group, Trans. Connecticut Acad. Sci., vol. 22, 1917, pp. 211–248 (229–233).

[387] Lemberg, J., Zeits. d. deut. geol. Gesell., vol. 40, 1888, p. 357. See also Steidtmann, E., Origin of dolomite as disclosed by stains and other methods, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 431–450.

[388] Lemberg's solution is prepared by boiling for 20 minutes a mixture of 4 grams $AlCl_3$, 6 grams extract of logwood, and 60 grams of water, with constant stirring and replacement of water lost by evaporation. After cooling and filtering it may be bottled for future use. Steidtmann diluted the standard preparation with 1200 cc. of water and obtained perfect results.

to the sites of deposition of the original materials of the present dolomites.[389]

Dolomites are known to be present in every geologic system, even those which are comparatively recent. Their greatest distribution is in the early Paleozoic and Pre-Cambrian systems.[390] Reasons for this distribution are given on later pages.

Modes of Occurrence of Dolomite

The modes of occurrence of dolomite whose origin may be ascribed to sedimentary processes are:

1. Dolomites of formational extent.
2. Dolomites interbedded with other rocks.
3. Dolomitized coral reefs.
4. Mottled limestones.
5. Nests of dolomite in calcite limestones.
6. Dolomite passing laterally into calcite limestone.

Dolomites of Formational Extent. Many Pre-Cambrian and early Paleozoic formations are dolomite or dolomitic limestones from top to bottom. Such also occur in the late Paleozoic and Mesozoic systems, but they are not so common, although they have large development locally, particularly in the Permian of southwest Texas and the Triassic and Jurassic in the Alps of central Europe. Dolomite limestones are rare in the Cenozoic. The thicknesses of individual formations range from less than 20 feet to more than 100. They are overlain and underlain in different instances by limestones, sandstones, or shales, and, in some cases, by other formations of dolomite.

Well known formations of dolomite are the Oneota and Shakopee of the upper Mississippi Valley, the Big Horn dolomite of Wyoming, the Niagara dolomites of the Great Lakes region, the Durness limestones of the Northwest Highlands of Scotland, the Triassic Schlern dolomites of the southern Tyrol, the Little Falls dolomite of the Mohawk Valley, the Knox dolomite of the Appalachians, the Potosi dolomite of the Ozark region, and the Capitan dolomite of southwest Texas. These extend over great areas and are of essentially similar composition throughout their distribution. None of these has been affected by regional metamorphism, and their characters have been attained by sedimentary conditions. Many of these dolomites are full of the dome-shaped structures built by calcareous algæ, and some

[389] Bauernschmidt, A. J., Jr., Lignite in dolomite, Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 517–520.

[390] Daly, R. A., First calcareous fossils and the evolution of limestone, Bull. Geol. Soc. Am., vol. 20, 1909, p. 165.

of them are oolitic. It is probable that the former contained magnesium carbonate at the time of formation, and such may also have been the case for the oolites, but it is not known that the latter are composed of magnesium carbonate as original material. A feature not infrequently occurring in dolomites which contain many algal structures is an appearance of brecciation. This is thought to be due to the breaking up of algal crusts, and recementation in those places where the fragments were washed together.

Dolomites Interbedded with Other Rocks. Individual beds of dolomite are known to occur interstratified with limestone, sandstone, and shale, and in rare instances with salt and gypsum; and such interbedding seems to be more common than generally supposed. The thickness of the individual beds of dolomite ranges from an inch or less to many feet, thin beds appearing to be more irregular and discontinuous than thicker ones. Particularly striking occurrences of the interbedding of sandstone and dolomite are those of the Kansas and Oklahoma "Red Beds," the Chugwater formation of Montana and Wyoming, and the Permian of England. In those of the Permian of Kansas and Oklahoma and the Chugwater of Montana and Wyoming the white dolomites form conspicuous bands around the red hills. Instances of the interbedding of limestone and dolomite have been described by Dale[391] in Vermont and elsewhere in New England; by Daly[392] in the Pre-Cambrian of British Columbia and Montana; by Leonard[393] from the Galena of Iowa; by Van Tuyl[394] in the Tribes Hill of New York, the Niagaran and Devonian of Iowa, and the St. Louis limestone near Little Rock, Missouri; by Ladd[395] in the St. Louis limestones in the vicinity of St. Louis, Missouri; by Mahnsen[396] in the Upper Jurassic of Germany; and by Vogt[397] in Norway.

In many of the above occurrences the contacts of limestone and dolomite layers do not always follow stratification planes, and the relationships in these cases are believed to represent pseudo-interstratification effects rather than true interbedding due to variations in the character of the original sediments. Some of the dolomites and the interbedded limestones are oolitic, and the oolites in each case are believed to have originally been formed of calcium carbonate. As a rule the internal structures of the

[391] Dale, T. N., The commercial marbles of western Vermont, Bull. 521, U. S. Geol. Surv., 1912, pp. 29–33.

[392] Daly, R. A., The limeless ocean of Pre-Cambrian time, Am. Jour. Sci., vol. 23, 1907, p. 110.

[393] Leonard, A. G., Iowa Geol. Surv., vol. 16, 1905, p. 249.

[394] Van Tuyl, F. M., op. cit., pp. 374–381.

[395] Ladd, G. E., Bull. 3, Missouri Geol. Surv., 1890, pp. 54–76.

[396] Mahnsen, M., Neues Jahrb., Beil. Bd. 35, 1913, pp. 277, et al.

[397] Vogt, J. H. L., Der Marmor, Zeits. prakt. Geol., 1898, p. 9.

dolomite oolites are not well preserved, and in some cases almost totally destroyed.

Dolomitized Coral Reefs. Examples of recent and near-recent dolomitized coral reefs have been described from the coral islands of the southern Pacific by Dana,[398] Skeats,[399] and others, and Branner[400] has reported a dolomitized reef rock in the "stone reefs" of Brazil. Probably the most notable examples of fossil coral-reef rock changed to dolomite are those in the Niagara limestones of the upper Mississippi Valley and the great Schlern limestones of southern Tyrol. Dolomitized reefs ordinarily do not have the shells and corals very well preserved.

Mottled Limestones. Mottled limestones might be considered as small nests of dolomite in calcite limestone. They have been described from the Carboniferous of south Wales as pseudo-brecciated[401] and Wallace[402] has used a similar term for Ordovician limestones of Manitoba. Peach and Horne[403] have described as probably dolomitized worm castings what appears to be this feature in the Croisaphuill limestone of the Northwest Highlands of Scotland. The mottling arises from the occurrence of patches of dolomite in the midst of calcite limestone. On a weathered surface the dolomite patches are usually yellowish to buff in color against the surrounding gray of the limestone and also have a sandy appearance. Due to the greater resistance they usually stand a little in relief. It is not known that a gradation exists between the non-dolomitized and fully dolomitized rock.[404]

With respect to origin, the mottling appears to be of two types: inorganic, in that the dolomitization appears to have spread outward from centers in the limestone not related to organic matter, and organic, in which organic matter may have served as centers.

Mottled limestones in which the dolomitization seems to have spread outward from centers of organic character have been observed by Van Tuyl[405] in the Tribes Hill limestones of the Mohawk Valley, in Division D of the Beekmantown limestone at Fort Ticonderoga, New York, in divisions

[398] Dana, J. D., Am. Jour. Sci., vol. 45, 1843, p. 120.

[399] Skeats, E. W., Bull. Mus. Comp. Zool., vol. 42, 1903, pp. 53–126.

[400] Branner, J. C., The stone reefs of Brazil, Mus. Comp. Zool., vol. 44, 1904, p. 265.

[401] Dixon, E. E. L., The geology of the South Wales coal-field, Pt. VIII, Mem. Geol. Surv. England and Wales, 1907, p. 10.

[402] Wallace, R. C., Pseudobrecciation in Ordovician limestones in Manitoba, Jour. Geol., vol. 21, 1913, p. 402.

[403] Peach, B. N., and Horne, J., The geological structure of the Northwest Highlands of Scotland, Mem. Geol. Surv. Great Britain, 1907, p. 379.

[404] Wallace, R. C., Recent work on dolomitization, Rept. Comm. on Sedimentation Nat. Research Council, 1927, p. 65.

[405] Van Tuyl, F. M., op. cit., pp. 345–357.

A and B of the Beekmantown and in the Chazy limestones at Shoreham, Vermont, and in the Beekmantown at several localities in Pennsylvania. Supposed inorganic centers of mottling occur in the Ordovician limestones of the Hudson Bay region, in the Chazy limestone on Valcour Island, Lake Champlain, and in the Galena limestone near Guttenberg, Iowa, etc. In Manitoba certain horizons of the Ordovician are dark-mottled with dolomite, whereas the Silurian and a part of the Devonian are fully dolomitized. Birse[406] has shown that the mottling forms a continuously connected pattern, both vertically and horizontally. Wallace[402] originally referred the mottling to dolomitization related to seaweeds, a view which is discarded by Birse, Wallace[404] concurring. Each patch of dolomite has a darker core suggesting a tube. It is possible that some annelid may be responsible for this and thus ultimately for the dolomitization. Certain fossils are dolomitized, whereas others are unaffected, it being suggested that the dolomitized forms were originally composed of a metastable form of calcium carbonate.

NESTS OF DOLOMITE IN CALCITE LIMESTONES. Nests of dolomite in calcite limestone were described from the Lahn district of Europe by Klipstein[407] as early as 1843. In more recent years Salomon[408] has noted the occurrence of nests and tongues of dolomite in the Ladinac limestone of the Alps, and Smith[409] found nests and chimney-like masses of nearly pure dolomite in the coral limestone of the Traverse group at Alpena, Michigan. Van Tuyl[410] has described boulder-like masses and lenses of dolomite surrounded by limestone in the St. Louis limestone in Illinois and Iowa and in the Spergen limestone near Belfort, Iowa.

DOLOMITE PASSING LATERALLY INTO CALCITE LIMESTONE. The lateral passage of dolomite into calcite limestone has been frequently reported, but it is thought that some of the cases have been based on incorrect correlations and it is not always certain that existing analyses are sufficient to warrant the statements that are made. Calvin states that in Delaware and Buchanan counties, Iówa, there are several areas of gray, unaltered Niagara limestone, ranging from a few square yards to several square miles in extent and up to 30 or more feet in thickness, which are entirely surrounded by massive, Niagara dolomite.[411] The time of the

[406] Birse, D. J., Dolomitization processes in the Paleozoic horizons of Manitoba, Trans. Roy. Soc. Canada, vol. 22, 1928, pp. 215–221.

[407] Cited by Bischof, G., Elements of physical and chemical geology, Eng. Transl., vol. 3, 1859, p. 185.

[408] Salomon, W., Die Adamellogruppe, Abh. k.-k. geol. Reichsanstalt, Wien, vol. 21, 1908, p. 408.

[409] Smith, R. A., Quoted by Van Tuyl, F. M., op. cit., p. 359.

[410] Van Tuyl, F. M., op. cit., pp. 359–361.

[411] Calvin, S., Iowa Geol. Surv., vol. 8, 1897, pp. 154, 218.

dolomitization has not been determined. Similar gradation from dolomite to limestone is reported in the Spergen Hill (Salem) and St. Louis limestones of southeastern Iowa;[412] in the Carboniferous limestone of County Kilkenny, Ireland;[413] in the Jurassic Korallenoolith of the Alpine country;[414] and in the Jurassic of France.[415]

The Origin of Dolomite[416]

There has been much discussion relating to the origin of dolomite, and several theories have been advanced. These fall into the three classes given below.

- Primary deposition theories
  - Chemical deposition
  - Organic deposition
  - Clastic deposition
- Replacement theories
  - Marine replacement
  - Ground-water replacement
  - Hot-water replacement
- Leaching theories
  - Leaching by surface waters
  - Leaching by marine waters

The origin of the dolomitic sediments may be studied from the points of view of the occurrence of dolomite in the unconsolidated sediments forming the present floor of the sea, the experimental production of dolomite under controlled physical and chemical conditions, and the geologic relationships of the dolomite limestones formed in the past.

PRIMARY DEPOSITION OF DOLOMITE. Search for sediments composed of dolomite in the unconsolidated deposits on the present floor of the ocean has given few results, since dolomite is rather conspicuously absent in the samples which have been dredged from the bottom of the sea. As a minor secondary mineral it has been reported in dredgings from shallow waters, and it has been identified as a secondary mineral of slight abundance which decreases with depth.[417] Its presence in oozes of the Red Sea has been sug-

[412] Van Tuyl, F. M., op. cit., pp. 364–365.

[413] Hardman, E. T., Proc. Roy. Irish Acad., 2nd ser., vol. 2, 1875–1877, p. 728.

[414] Wichmann, R., Kurze Mitteilung über ein neues Vorkommen von Dolomitisierung am Greitberg bei Holzen, Monatsb. d. deut. Geol. Gesell., vol. 61, 1909, pp. 392–394.

[415] Pfaff, F., Pog Annalen, 1851, p. 471, cited by Van Tuyl, op. cit., p. 371. See also pp. 371–381.

[416] In connection with theories relating to the origin of dolomite, the reader should consult Steidtmann, E., Evolution of limestone and dolomite, Jour. Geol., vol. 19, 1911, pp. 323–345, 393–428; Van Tuyl, F. M., The origin of dolomite, Iowa Geol. Surv., vol. 25, 1914, pp. 251–422; Van Tuyl, F. M., The present status of the dolomite problem, Science, vol. 44, 1916, pp. 688–690.

[417] Böggild, O. B., Report of the Danish Oceanographical Expeditions 1908, 1910, vol. 1.

gested by chemical analyses, and on the Seine Bank, east-northeast of the Madeira Islands, it was found to be a part of the cement of pieces of fossiliferous limestone dredged from a depth of about 150 meters. Deposition of lime carbonate has ceased at this locality, and the specimens are believed to be of Pleistocene age.

As previously stated, the shells and tests of certain existing marine organisms contain some magnesium carbonate, which rises as high as 25 per cent in some calcareous algæ. The tests of certain species of crinoids and Alcyonaria living in tropical seas contain more magnesium than has been found in the tests of forms living in colder waters, and the analyses of the tests of some of the foraminifera, crustacea, and algæ are to the same point.[418] The magnesium carbonate in the different tests and shells does not seem to be in the form of dolomite, but probably exists in solid solution in the calcite or is isomorphous therewith. Some may be in the form of free magnesium carbonate or magnesium hydroxide. In order for recrystallization of these tests to produce normal dolomites, it would be necessary to remove some of the calcium carbonate by leaching, or introduce some magnesium carbonate.

The facts cited indicate that magnesium carbonate and possibly other compounds of magnesium occur on the present sea floor in such quantities that addition of some magnesium carbonate or subtraction of some calcium carbonate is essential before dolomite deposits can result from these materials.

The physical and chemical conditions which lead to the precipitation of magnesium carbonate in modern oozes are not well known. It is probable that a combination of various factors is essential, among which the kind and quantity of substances dissolved in water, the temperature, and the pressure, may be important. The causes leading to the occurrence of magnesium carbonate in the tests of organisms are also unknown. Perhaps they are physiological, but little is known relating to the utilization of magnesium by organisms. As stated above, its occurrence in shells appears to be related to temperature, and its presence in algal secretions probably is due to precipitation of magnesium carbonate caused by extraction of carbon dioxide.

Irving[419] has investigated the precipitation of calcium and magnesium by increasing the alkalinity of sea water, and he states that

[418] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of marine invertebrates, Prof. Paper 124, U. S. Geol. Surv., 1922, p. 61.

[419] Irving, L., The precipitation of calcium and magnesium from sea water, Jour. Marine Biol. Assoc. United Kingdom, vol. 14, 1926, p. 441; in Wallace, R. C., Recent work on dolomitization, Rept. Comm. on Sedimentation, Nat. Research Council, 1927, p. 65.

If the increase in alkalinity results from increase in free base alone, the magnesium is rapidly precipitated as the $_pH$ rises above 10. Calcium precipitation likewise occurs, but more slowly. If the precipitation occurs from the addition of carbonates (changing the $_pH$ then by electrolysis), magnesium precipitation follows the $_pH$ curve, indicating its occurrence as a function of hydroxyl ion exclusively. Calcium is precipitated chiefly by increase of carbonate ion concentration. The explanation is of course in the fact that $CaCO_3$ is relatively insoluble, $MgCO_3$ relatively soluble. $Ca(OH)_2$ on the contrary is quite soluble as compared with the insoluble $Mg(OH)_2$. There is a possibility of salt waters naturally approaching a $_pH$ value of 10, permitting the precipitation of both calcium and magnesium. The conditions would determine the ratio of calcium to magnesium. In waters whose alkalinity is produced by free carbonate, the calcium would far exceed magnesium in the precipitate. Were the alkalinity induced by a process removing carbonates and leaving free base, magnesium precipitation would correspondingly increase.

It is not known that dolomite would result.

Considerable has been written with respect to the primary precipitation of dolomite in sedimentary environments, but it must be kept in mind that no observations have been made showing the occurrence of such in modern seas. The work of students prior to 1916 is summarized by Van Tuyl[420] and may be consulted in his work on dolomite. Götz[421] referred the dolomites of the Lorraine Muschelkalk to a primary origin, the sediments being deposited in shallow waters from colloidal magnesium and calcium carbonates temporarily held in suspension by protective organic colloids, and finally precipitated in intimate mixture suitable for crystallization into dolomite. It is not known to what extent the two carbonates are thus carried, and hence the consideration seems entirely hypothetical.

Dale[422] referred the dolomites of the Stockbridge limestone of western New England and eastern New York to an origin by primary deposition. Trechmann concluded that the excellent preservation of delicate fossils, hollow spaces left by crystalline anhydrite aggregates, oolites with calcite nuclei, and calcareous fossils in the midst of a dolomite matrix in the Permian Durham limestones of England require direct deposition of dolomite. He found considerable replacement of calcite shells and parts of a bryozoan reef.[423] Green[424] referred the Permian dolomites of Yorkshire to the same origin.

[420] Van Tuyl. F., The origin of dolomite, Iowa Geol. Surv., vol. 25, 1916, pp. 264–270, 318–324.

[421] Götz, G., Über die Entstehung des Dolomits der Muschelkalkschichten nördlich des Lothringer Hauptsattels, und über den Einfluss von Kolloidenphasen auf der Bildung von Dolomit überhaupt, Geol. Rundsch., 1921, vol. 12, p. 138.

[422] Dale, T. N., The lime belt of Massachusetts and part of eastern New York and western Connecticut, Bull. 744, U. S. Geol. Surv., 1923, pp. 51–56.

[423] Trechmann, C. T., On the lithology and composition of Durham magnesian limestones, Quart. Jour. Geol. Soc., vol. 70, 1914, pp. 232–265 (251–253).

[424] Green, A. H., On the method of formation of the Permian beds of North Yorkshire, Geol. Mag., vol. 9, 1872, pp. 99–100.

The common occurrence of dolomite in the deposits of desiccating basins suggests the possibility that it may be formed directly from the carbonates precipitated because of evaporation. On the other hand, there seems to be little or nothing in these dolomites, or the associations, which might not have been produced by replacement. The best that may be said is that no examples of primary deposition of dolomite are known and that primary deposition of this sediment lies entirely within the realm of theory.

Laboratory production of dolomite has been of little assistance in solving the problem of its primary deposition. According to Merwin:[425]

Very little to assist in the interpretation or guidance of field studies has been found out by experimentation concerning the chemical relations of dolomite, although dolomite has been reported as a laboratory product under a variety of conditions.[426] The geological significance of the experiments is slight because geological conditions have not been met, and no basis of extrapolation to such conditions is evident.

The recent work described by G. Adolf, M. Pulfrich, and G. Linck[427] was the most systematic yet done, but large quantities of ammonium salts as well as elevated temperature and pressure were used to bring about the formation of dolomite, and no equilibrium relations were established. A porous spherulitic calcium carbonate (probably calcite),[428] apparently more reactive than more coarsely crystalline material, was employed. Some relations between dolomite limestones and fresh waters—cold and hot—penetrating into and issuing from them are considered by H. Klähn.[429]

In some cases the identification of the product has been questionable, and in no case have the possible effects of solid solution of magnesium or calcium carbonates been considered.[430] In sediments which have not been much altered excess of magnesium carbonate would not be expected, but in rocks containing both dolomite and calcite the dolomite crystals sometimes contain perhaps 20 per cent excess of calcium carbonate besides ferrous and manganous carbonates.[431]

Qualitatively by staining methods iron has been found in all of a large number of dolomites tested by E. Steidtmann.[432] The iron is probably present not as siderite but as ferrous calcium carbonate strictly isomorphous with dolomite. This compound may prove easier to prepare, especially near marine temperatures, than dolomite, for no hydrate of ferrous carbonate analogous to the comparatively soluble $MgCO_3 \cdot 3H_2O$ is known. Solid solutions of dolomite and this compound might then be obtained.

Mitchell[433] obtained crystals which seem to have been dolomite by using

[425] Contributed by H. E. Merwin.

[426] Clarke, F. W., Data of geochemistry, Bull. 695, U. S. Geol. Surv., 1920, p. 520.

[427] Neues Jahrb. f. Min., Centralblatt, 1921, p. 545.

[428] Johnston, J., Merwin, H. E., and Williamson, A. D., The several forms of calcium carbonate, Am. Jour. Sci., vol. 41, 1916, p. 486.

[429] Chem. Erde, vol. 3, 1928, pp. 454–587.

[430] Spangenberg, K., (Z. Kryst., 52, 561) gives the specific gravity of supposedly pure artificial dolomite as 2.825, whereas numerous determinations indicate 2.87 for pure natural crystals.

[431] Ford, W. E., op. cit., p. 243; Koller, P., Neues Jahrb. f. Min., Beil. Bd. 42, 1919, p. 487.

[432] Steidtmann, E., Bull. Geol. Soc. Am., vol. 28, 1917, p. 431.

[433] Mitchell, A. E., Studies on the dolomite system, Jour. Chem. Soc., vol. 123, 1923, pp. 1055–1065, 1887–1904.

500 cc. of "artificial sea water," lacking magnesium chloride and calcium carbonate, which was slowly stirred in a beaker into which solutions of N/25-magnesium chloride and saturated calcium bicarbonate were allowed to enter drop by drop on opposite sides of the beaker until 100 cc. of each had been added. This produced no precipitation. The solution was then made alkaline by adding N/20-sodium carbonate. A precipitate appeared six hours later, and this had increased to twice its bulk after a week. The particles of this precipitate were irregular and so small as to prevent accurate determination of optical characters beyond the fact that the refractive index was slightly greater than 1.69 and the birefringence was very strong. The precipitate was neither hydrated nor basic and analyzed CaO, 26.45-26.50; MgO, 25.10; and CO_2, 48.58 to 48.61 per cent. This approaches the theoretical composition of dolomite, but with an excess of magnesium carbonate. The conditions employed by Mitchell are not unlike those existing in nature, and hence it is to be expected that substances like those obtained by him may be precipitated from natural sea water.

Primary deposition of clastic materials composed of dolomite may be assumed to have occurred many times during past geologic periods, and such probably is now taking place along some shores and in other environments, as dolomite terranes of arid regions, sea and lake coasts, and some river channels must locally be yielding clastic materials to the agents of transportation. This suggestion seems to have first been made by Lesley[434] to explain dolomites exposed in a quarry on the west bank of the Susquehanna River opposite Harrisburg, Pennsylvania, Phillipi[435] explained impure dolomites in the Muschelkalk of Germany as having originated in this way, and Grabau[436] appealed to this method of origin for beds of dolomite in the New York Salina. It should not be assumed, however, that the explanation of clastic origin for these strata is necessarily correct.

Dolomite Due to Replacement and Leaching. Replacement of sediments to form dolomite may take place before or after consolidation, by marine waters or ordinary ground waters, or by hot waters derived from the earth's interior. Numerous writers have appealed to marine waters to effect the transformation of deposits of calcium carbonate to the double carbonate of calcium and magnesium, and this view seems to have the greatest support at the present time. Steidtmann[437] summarized the data relat-

[434] Lesley, J. P., Second Geol. Surv., Pennsylvania, 1879, p. 311.

[435] Phillipi, E., Lethæa geognostica, vol. 2, 1908, p. 31.

[436] Grabau, A. W., Principles of stratigraphy, 1913, p. 76; Bull. Geol. Soc. Am., vol. 24, 1913, p. 399.

[437] Steidtmann, E., op. cit., 1917, p. 440.

ing to dolomitization by replacement of calcium carbonate on the sea bottom under the four headings of:

Relations of dolomite grains to bedding.
Relations of dolomite to fossils.
Relations of dolomite grains to each other and to calcite grains.
Relations of dolomite to previous marine structures.

From the point of view of the relations of dolomite grains to bedding, he finds that the bunchy, irregular distribution of the dolomite in many limestones harmonizes best with replacement before consolidation.

Fossils in dolomite usually are rare and poorly preserved and very commonly consist of molds with the original organic matter absent. As shown by Weller[438] and observed by the author, the fossils preserved in dolomites are like those contained in associated calcite limestones, and the facts seem to indicate that the environmental conditions existing during the deposition of the beds which are now dolomites were not inhibitive to the presence of organisms. Furthermore, many fossils preserved in dolomites are best preserved in calcitic or silicified portions, whereas in the surrounding dolomite, fossils are rare or absent and those present are poorly preserved, indicating that in the process of dolomitization the fossils were destroyed. If this is accepted, it places the time of dolomitization as contemporaneous with, or subsequent to, silicification. Many fossils in dolomites show that they were invaded by the dolomite crystals as the latter were forming. Other fossils are completely surrounded by dolomite, and cavities within them are filled with crystals of this mineral. As pointed out by Steidtmann[439] and again by Wallace,[440] the destruction of fossils by dolomitization seems to be selective in that those composed of aragonite are apparently more susceptible to destruction than those whose shells are calcite.

The dolomite grains seem to be commonly related to the calcite grains under conditions which are best explained on the basis that development of the former occurred when the materials were soft, but as the grains of each mineral are mutually closely interlocking and commonly anhedral, sufficient rigidity must have been present to prevent growth of dolomite particles with crystalline boundaries. Contacts between dolomite and calcite grains are commonly sharp, and, according to Steidtmann, there is no evidence indicating that the dolomite grains obtained their calcium from calcite.

[438] Weller, S., Bull. Geol. Soc. Am., vol. 22, 1911, pp. 227–231.
[439] Steidtmann, E., op. cit., 1917, p. 441.
[440] Wallace, R. C., Lectures, Univ. of Wisconsin, 1930.

The fact that numerous dolomites are unrelated to cracks, bedding planes, and other channels of underground water circulation, but, instead, are in positions distant from influence of such circulation, supports the view that the change to dolomite took place while the sediments were still soft and under the influence of the waters of deposition. However, it is of course well known that there are numerous examples of dolomitization which can be proved to have been accomplished after the original materials had become cemented and indurated, as, for instance, the dolomitization due to hydrothermal action described by Hewett,[441] but such in no way are competent to explain the wide-spread occurrences of dolomites in unaltered deposits. .

The marine alteration theory for the formation of dolomite invokes one or both of two processes. One of these postulates that the magnesium carbonate necessary to form the dolomite was derived from the overlying sea water, in which magnesium exceeds calcite in the ratio of 3 to 1; either by the magnesium uniting directly with the already deposited calcium carbonate to form dolomite, or by some of the calcium carbonate being taken into solution and replaced by a chemically equivalent quantity of magnesium carbonate. Steidtmann[442] states that the formation of dolomite by the substitution of one molecule of magnesium carbonate for a molecule of calcium carbonate has not been checked by observation, but there are certain facts suggesting that this may occur. A second process postulates that uncombined magnesium carbonate exists in calcareous sediments and that crystallization of these sediments leads to the formation of the double salt. Except in connection with deposits resulting from algæ and a few invertebrates, however, little magnesium carbonate occurs in modern sediments, thus making it difficult and probably impossible for entire beds and formations of dolomite to originate in this way; some addition of magnesium carbonate or extensive leaching of calcium carbonate must take place.

It has long been known that some comparatively recent sediments originally deposited as calcium carbonate or with calcium carbonate as the most important constituent, have become dolomitized, or at least rich in magnesium carbonate, a short distance beneath the surface, and not an extremely long time after their deposition. The well drilled on Funafuti Atoll is instructive on this point. The core and samples from this well showed 4.33 per cent magnesium carbonate at the depth of 4 feet from the surface and 16.4 and 16 per cent at 15 and 25 feet respectively, at which

[441] Hewett, D. F., Dolomitization and ore deposition, Econ. Geol., vol. 23, 1928, pp. 821–863; Dolomitization in southern Nevada, Bull. Geol. Soc. Am., vol. 35, 1924, pp. 124–125.

[442] Steidtmann, E., op. cit., 1917, p. 448.

depths the concentrations seem to have been due to leaching. At the depth of 35 feet from the surface the materials from the well carried 9.1 per cent magnesium carbonate. So far as determinable at that time, none of this was in the form of dolomite. Below the depth of 35 feet the per cent of magnesium carbonate was small to the depth of 637 feet, ranging from less than 1 per cent to 6.8 per cent, being 2.44 at 637 feet and averaging 3.33 per cent. As the material from this portion of the hole in few cases was a solid core and was mostly in the form of small loose particles, it is possible that the magnesium carbonate content was greater than shown by the material analyzed. At 638.9 feet the per cent of magnesium carbonate rose from the 2.44 per cent at 637 feet to 20.44 per cent, and with some fluctuations there was a general increase to the final depth of 1114.5 feet, the greatest quantity being found at 950 feet, where there was 43 per cent. The average for the depths below 638.9 feet approximated 40 per cent. At no place did the composition attain that of normal dolomite.[443] From 638 feet to the bottom the core consisted of dolomite with some calcite. Calcite was rare or absent from 650 to 820 feet, 875 to 1050 feet, and from 1050 feet to the bottom. As less calcite was usually shown than indicated by the chemical composition, some was either isomorphous or in solid solution in the dolomite, although it might have been disseminated therein in microscopic particles.

In some cases it was obvious that the dolomite was an addition to the mass of the rock, as it now fills original pore space. In other cases it was seen replacing calcite, secondary calcite being the first to go. Aragonite was common in samples from the upper portion of the well; it began to disappear about 100 feet from the surface; it was practically gone at 150 feet; and none was detected below 220 feet. No aragonite was seen in association with dolomite.[444] The aragonite disappeared by conversion to calcite and by solution, secondary aragonite disappearing first.

As many of the organic contributions to the materials of the reef rock were of algal origin, and in some of them magnesium carbonate is a common constituent, the relationship probably has causal implications.

The column of rock shown in the Funafuti well may be divided into three zones: an upper, to the depth of 25 feet, whose composition is largely due to the organic matter of which it is composed, but slightly modified by removal of some material through leaching; a middle zone from 25 to 637 feet, of which the rock is calcite (some aragonite in upper part) limestone con-

[443] Judd, J. W., in Sollas, et al., The atoll of Funafuti, Rept. of Coral Reef Committee of Roy. Soc. London, 1904, pp. 364–365. Skeats (Skeats, E. W., Bull. Mus. Comp. Zool., vol. 42, 1903–1905, pp. 53–126) also found such to be the case in the limestones of Pacific and Indian islands.

[444] Cullis, C. G., The atoll of Funafuti, Roy. Soc. London, 1904, p. 403.

taining an average of 3.33 per cent magnesium carbonate which does not seem to be in the form of dolomite; and a bottom zone from the depth of 639 feet to 1145 feet of which the rock is dolomite or dolomitic limestone, with the change from calcite to dolomite limestone very sharp, the per cent of magnesium carbonate rising from 2.44 to 20.44 per cent in less than 2 feet. It was found that dolomite was commonly not present until the quantity of magnesium carbonate was about 15 per cent, as calcite seems able to include this much and retain its crystalline form.[445] When the magnesium carbonate exceeded 15 per cent, crystals of dolomite were found to make their appearance.

A well at Key West in the Florida Keys passed through calcareous materials with a considerable range of magnesium carbonate, the greatest quantity, 14.07 per cent, being at 775 feet, where the calcium carbonate was 83.12 per cent. The minima, 0.61 and 0.63 per cent, were at 25 and 1400 feet respectively. The average for all depths was 3 per cent.[446] It does not seem to be recorded that any dolomite was found in this well.

Studies of these two columns indicate that some leaching of calcium carbonate has occurred. The Funafuti column shows that actual additions of dolomite have been made to parts of the rock, as this mineral has been deposited in cavities with its crystals resting upon and enclosing scalenohedra of secondary calcite. Replacement of calcite by dolomite and recrystallization and dolomitization of calcareous muds forming euhedral crystals of dolomite are shown. The variations in the magnesium content can only partially be referred to presence of magnesium in organic matter, and it seems absolutely essential that some magnesium carbonate must have been introduced and possibly some calcium carbonate subtracted. Bearing on the problem, an instructive illustration is given by Hume.[447] Sea water washing against the Graving Dock at Alexandria, Egypt, developed curious coralloid-appearing growths along fissures in the lower part of the dock. These proved to be composed of calcium and magnesium carbonates produced by the attack of magnesium salts in the sea water on the lime in the concrete blocks.

Fundamental to the problems of leaching and replacement of calcium carbonate to enrich resulting materials in magnesium carbonate, and the problem of the simultaneous deposition of the two carbonates, are their

[445] Skeats, E. W., The chemical and mineralogical evidences as to the origin of the dolomites of Southern Tyrol, Quart. Jour. Geol. Soc., vol. 61, 1905, pp. 97–141 (131, 135); Skeats, E. W., op. cit., 1903–1905, p. 114.

[446] Judd, J. W., op. cit., p. 374, analysis by Steiger. Analyses of the rocks of raised reefs of different parts of the Indian and Pacific oceans were made by Doctor E. W. Skeats and may be found in Bull. Mus. Comp. Zool., vol. 42, 1903, pp. 53–126.

[447] Hume, W. F., Review of Walther's "Das Gesetz der Wüstenbildung," Geol. Mag., vol. 51, 1914, pp. 18–20, 73–78.

relative solubilities. These naturally must differ with the characters of the dissolving waters and the composition of the atmosphere. It was Judd's[448] conclusion that in sea waters containing carbon dioxide under existing atmospheric pressure, solution of calcium carbonate proceeded more rapidly than of magnesium carbonate. Skeats[449] formulated the same conclusion, but states further that under a pressure of five atmospheres fresh water containing carbon dioxide dissolves the magnesium carbonate of dolomite and has little effect on the calcium carbonate. If these conclusions are correct, there must be some pressure between one and five atmospheres where the two carbonates may be precipitated together, possibly to form dolomite simultaneously, or later when recrystallization begins. At lesser atmospheric pressures calcium carbonate may be leached away or replaced in part by magnesium carbonate. However, the data relating to the relative solubilities of the two carbonates are not wholly in accord. Goldman[450] found that calcareous sands on the shores of the Bahamas exposed to the action of sea water had experienced decrease rather than increase in magnesium carbonate, and the same result was obtained in a specimen of *Acropora* exposed for 34 years to sea water. Leather and Sen[451] state that magnesium bicarbonate is much more soluble in water than calcium bicarbonate, that calcium carbonate becomes practically insoluble in the presence of an excess of magnesium bicarbonate, and a mingling of solutions of calcium carbonate and of magnesium carbonate results in the precipitation of most of the former; and that if a "mixture of calcium and magnesium carbonates is subjected to the action of carbonic acid and water, the calcium carbonate is largely or wholly prevented from dissolving." Dolomite was found to dissolve in carbonated waters apparently in the form of the double carbonate.

It seems probable that various factors must be considered in problems of dolomitization, among which pressure, composition of the atmosphere, temperature, composition of the water, rate of deposition, and life processes are most important. Several of these, no doubt, have been changed during geologic time.[452]

[448] Judd, J. W., op. cit., pp. 378–383. See references cited by Judd.

[449] Skeats, E. W., op. cit., 1905, pp. 134–136.

[450] Goldman, M. J., Publ. 344, Carnegie Inst. Washington, 1922, p. 39.

[451] Leather, J. W., and Sen, J., The system water, calcium carbonate, carbonic acid, Mem. Dept. Agric. India, Chem. Ser., vol. 1, 1909, pp. 117–131; The systems:—(A) Water, magnesium carbonate and carbonic acid, (B) Water, calcium carbonate, magnesium carbonate and carbonic acid, op. cit., vol. 3, 1914, pp. 205–234. See also Wells, R. C., The solubility of magnesium carbonate in natural waters, Jour. Washington Acad. Sci., vol. 5, 1915, p. 491; ibid., Jour. Am. Chem. Soc., vol. 37, 1915, pp. 1704–1707; ibid., the solubility of calcite in water in contact with the atmosphere and its variation with temperature, Jour. Washington Acad. Sci., vol. 5, 1915, pp. 616–622.

[452] Rozza, M., Centralbl. f. Min., 1926, pp. 217–239.

Places of Origin of Unmetamorphosed Sediments Which Are Now Dolomites. It seems probable that most sediments which are now dolomites were formed under marine or saline lake conditions. This seems proved by the character of the contained fossils. The close association of these dolomites with strata of unquestionably marine origin points to the same conclusion. Equal assurance cannot be had for the extensive Pre-Cambrian dolomites, as these, except for algal structures whose life environment is not certainly ascertainable, are without known fossil content. Their general geologic relationships, however, are such that deposition in a large body of water may be considered established. The fact that dolomite rather than calcite limestone commonly occurs in association with salt and gypsum suggests that abnormally salty waters favor the deposition of the former. Origin in shallow water seems probable. Van Tuyl[453] gave data tending to show that dolomitization occurs in shallow water and that equivalent strata deposited in deeper waters remain calcite limestones. The postulate of shallow water was also made by Tarr,[454] who argued that formation of dolomite is directly dependent upon shallow-water conditions, either in shallow continental seas or lakes. He also postulated that such conditions were essential for sufficient concentration of magnesium salts.

A fact of interest in the distribution of dolomites and one which may have bearing on their origin lies in their regional distribution in comparison with the distribution of calcite limestones of the same age. The Ordovician and Silurian strata of the upper Mississippi valley are dominantly dolomite, whereas rocks of the same age of the St. Lawrence and Baltic regions are dominantly calcitic. The causes of these differences must be sought in differences in environmental conditions. The deposits of the St. Lawrence and Baltic regions seem to be thicker than the equivalent deposits of the upper Mississippi valley; the latter may have been of slower accumulation and, possibly, of shallower water. This may be a clue to the situation. Perhaps the relations of the two bottoms with respect to the base level of deposition were such that in the upper Mississippi valley the bottom was built up to a steadily but slowly rising base level of deposition, while the other bottoms accumulated most of their sediments at some distance below this level, so that each successive deposit remained exposed for a short interval. The former condition would favor leaching and replacement, the latter not. It should be noted that mud-cracked dolomites occur in the Richmond on the east shore of Lake Winnebago in Wisconsin and in the basal beds of the Oneota dolomite in several localities. This indicates extreme shallowness of water and slow deposition.

[453] Van Tuyl, F. M., Depth of dolomitization, Science, vol. 48, 1918, pp. 350–352.

[454] Tarr, W. A., A possible factor in the origin of dolomite, Science, vol. 51, 1920, p. 521.

The occurrence of few fossils in many dolomites and the extremely fine grain of some of them may have some bearing on the environment of origin. The fewness of fossils, however, may indicate their destruction in the intestinal and masticating organs of scavengers or they may have disappeared through dolomitization; in the latter case they would have little meaning with respect to environment. The fineness of grain may be due to fineness of the original precipitates, to wave grinding, or perhaps to grinding by organisms.

The geologic and other relationships which have been presented on previous pages afford the basis for the following provisional conclusions relating to the origin of dolomite: (1) Most dolomite sediments were formed in marine waters. (2) The replacement of calcium by dolomite and the enrichment in magnesium through leaching of calcite are important factors in the formation of dolomite, and they are the only processes which appear to be supported by evidence; this replacement and leaching are believed to have been done by marine waters before the sediments were completely consolidated; some dolomites may have originated from direct chemical or organic precipitation, but there is little proof therefor. (3) Clastic sediments may locally give rise to dolomite. (4) The conditions favorable for dolomitization appear to be rather distinct from those which do not favor it, and the range of conditions which permit both calcium carbonate and dolomite to form and remain stable side by side are rather limited. (5) The common presence of ferrous iron compounds in many dolomites suggests that they were formed under reducing conditions.

The formation of dolomite through replacement of calcium carbonate is proved by the following facts:

a. The complete replacement of calcium carbonate shells and tests by dolomite with or without modification of the form of the shell. As a rule, the original form is poorly reproduced or nearly obliterated by replacement. In some instances entire coral reefs have been replaced.

b. The partial replacement of calcium carbonate shells by dolomite. The invading dolomite grains are sharp rhombs where they are in contact with calcium carbonate, but where they are in contact with their own kind they are anhedral.

c. The view is supported by the irregular and bunchy distribution of dolomite in some limestones, the dolomite grains in some cases being clustered around worm holes or around and within shells.

In the cases of the shells, the dolomite cannot be explained in any other way than by replacement. The clustering about worm holes and shells may have been caused by chemical precipitation, but there is no proof that such was the case. It is difficult to understand the geologic occurrences of most dolomites on the basis of original precipitation. They may be

explained as a consequence of replacement assisted by leaching of calcium carbonate.

It has been commonly assumed that in the formation of dolomite by replacement, there is an increase in the porosity of the rock formed. It has been assumed that the replacement takes place according to the following reaction:

$$2CaCO_3 + MgCO_3 = CaMg(CO_3)_2 + CaCO_3 \text{ in solution}$$

a reaction involving a shrinkage of 12.30 per cent in volume. Many dolomites are porous and cavernous, and this characteristic has been assumed to be typical of all dolomites and to have arisen through replacement after solidification. However, many dolomites have more than the required pore space, while others in essentially horizontal positions have less than 1 per cent. It is difficult to refer these variations to replacement alone. Shells which have undergone partial or complete replacement by dolomite in numerous instances show no decrease in volume, and it is obvious that field observations give little support to the view that dolomitization involves a decrease in volume. Although it has not been proved that the porosity of some dolomites is due to replacement, it is probable that a part of it may arise in this way; but there are many other factors which determine pore space, among which are the physical characters of the particles composing the original calcite sediments, the cementation, the leaching subsequent to deposition, and the pressure to which the sediments have been subjected.

It is possible that enrichment in magnesium carbonate may be connected with the relation that the deposited sediments bear to a base level of deposition. Bottoms of calcium carbonate built to this level would be subjected to leaching and replacement for a long time, provided the waters were not already high in calcium carbonate. This might lead to the formation of a magnesium-rock layer or bed at the top of the sediment. If the rise of sea level were of such a rate that the bottom would be built to the level of no deposition bed by bed, enrichment by replacement, or leaching, or both, would occur bed by bed until a more rapid rise of sea level permitted more rapid and continuous deposition. Supplementary evidence in this respect is the fact that many dolomites contain an abundance of algal remains and most of them bear evidence of shallow-water deposition.

It has been suggested that the replacement of the calcium carbonate is brought about by ground water after the sediments become consolidated and are lifted above sea level,[455] but the fact that formational dolomites,

[455] Van Hise, C. R., A treatise on metamorphism, Mono. 47, U. S. Geol. Surv., 1904, pp. 804–808.

dolomites interbedded with limestone, and dolomite occurring as nests and irregular bodies in limestones are not related to the major openings accessible to ground water, to ground-water level, or the other features of ground-water circulation, but are related to such primary marine features as worm borings and shells, very strongly opposes the suggestion. It is true that dolomite veins and replacements adjacent to veins are due to the work of ground water, but this type of occurrence of dolomite bears about the same relation to the dolomite formations as do quartz veins to sandstone and quartzite formations in which they occur.

Likewise, the view that the dolomites are due to ground-water leaching has little or nothing in its support so far as the dolomite formations are concerned. It is true that there is local enrichment in dolomite due to ground-water leaching, but such occurrences are of very limited extent, and it would be impossible for formational bodies and interbedded dolomites and limestones to develop in this way.

Replacement by hydrothermal and pneumatolytic action has also been suggested. Such is important locally, but evidence of such action can in no way explain the widespread, unaltered dolomite formations and other occurrences of dolomite in unaltered deposits.

Clastic dolomite sediments are being deposited about those coasts where dolomites are undergoing erosion. Thus, on the beaches of some of the Mingan Islands in the Gulf of St. Lawrence the sands are composed of dolomite, and such probably occur elsewhere. The extent of deposits of this character appears never to have been determined. To explain dolomite formations in this way, however, is no solution, as a dolomite formation must be assumed from which the clastics may be derived. That dolomites of this origin exist in the geologic column is extremely probable.

The conditions which favor dolomitization in the sea appear to be rather sharply distinct from those which do not permit it. This is shown by the great abundance of nearly pure dolomites containing less than 10 per cent calcite, and of limestones with less than 10 per cent dolomite, contrasted with the relative scarcity of beds containing nearly equal quantities of both calcite and dolomite. Out of 1148 analyses of limestones and dolomites from all parts of the United States and representing all geologic systems, nearly 500 are limestones with less than 10 per cent dolomite. The dolomites with less than 10 per cent calcite number about 300. About 100 limestones contain between 10 and 20 per cent dolomite. A similar number of dolomites contain from 10 to 20 per cent calcite.[456] Less than 20 analyses show equal quantities of calcite and dolomite. Were the border zone be-

[456] These data were obtained from Doctor E. Steidtmann.

tween conditions favorable and unfavorable to dolomitization broad, beds containing mixtures of dolomite and calcite should be nearly as common as the pure dolomites and pure limestones.

That the sedimentary dolomites were generally and perhaps universally formed under reducing conditions is shown by the consistent presence of ferrous iron in a large number of dolomites which have been tested qualitatively. Such compounds, however, are not peculiar to dolomite, as they also are present in many limestones, shales, and sandstones. Since ferrous iron is easily oxidized, reducing conditions are necessary for its formation and preservation, and its presence negatives the view that the dolomites developed through replacement by ground water. The quantity of ferrous iron (estimated as the carbonate) in dolomites is known to range from less than 1 per cent to about 10 per cent. The number of quantitative tests on record, however, is small compared with the large number of dolomite formations.

Although the ferrous iron of dolomite in dolomitic sediments shows that the dolomite was formed under reducing conditions, the fossils of benthonic organisms in these same sediments show that the waters over the bottom contained sufficient oxygen to sustain them. Moreover, there is nothing in the fossil shells of most dolomites indicating that the conditions were greatly different from those where limestones resulted. These facts suggest that the ferrous carbonate did not develop on the surface of the bottom, but in the sediments where the decaying organic matter gave rise to reducing conditions.

Summary

With respect to the relative importance of phases of environment other than those to which reference has been made, essentially nothing is known, and even in the cases of those considered, the conclusions are largely theoretical. It is known that most, if not all, dolomites were formed in shallow water, but whether this is an essential condition is not proved. Most limestones were also formed in shallow water.

The effects of the concentration of the sea water and the gaseous content of the water are uncertain. The fossils of many dolomites do not indicate waters different from those in which the limestones were deposited. The calcareous sediments of desiccation deposits are commonly dolomitic and in many cases contain few fossils.

Dolomitic sediments appear to have usually been formed in warm seas, but the same is true with respect to limestones. Magnesia of organic secretion appears to have greater development in warm than in cold waters.

The results of past studies of the origin of dolomite suggest that the

following subjects of investigation may serve as valuable leads to further progress:

1. The extent of dolomitization in the seas, especially where reducing conditions prevail. Examination of sediments beneath the sea floor.

2. Experiments should be made on the production of dolomite under reducing conditions in the presence of ferrous iron in solution. These experiments should be under controlled physical and chemical conditions, and the conditions should simulate those in the sea so far as possible.

3. Studies should be made of the geologic relations of the dolomitic sediments, particularly with respect to the environmental conditions under which the sediments originated. Efforts should be made to determine the depth of water, the position of the bottom with respect to continuous deposition, the concentration of the water, and the temperature. No theory of the origin of dolomite can be complete until the environments of deposition are thoroughly understood.

The Carbonaceous Sediments

BY DAVID WHITE[457]

THE OCCURRENCE OF CARBONACEOUS SEDIMENTS

Definition

The carbonaceous sediments, as here understood, embrace sedimentary deposits containing plant and animal residues and products, including both original substances and subsequent chemical derivatives, the composition of all of which is chemically organic. The organic debris may have been carbonized (coalified) or "bituminized;" in either case the remains, as well as their derivative products found in the sediments, are characterized by the relative prominence of carbon, which is either "free" or joined with hydrogen in "hydrocarbon" union.

Carbonized or "bituminized" organic matter—there is no clear chemical distinction between carbonaceous and bituminous sediments—occurs in the oldest, recognizable sedimentary deposits, and throughout the geologic column it is present in the deposits of every environment. Carbonized wood, twigs, leaves, fruits, seed coats, algal thalli, mosses, etc., are readily recognized; but, in general, the vastly greater parts of the carbonaceous sediments are invisible to the unaided eye. They consist of minute to ultra-microscopic vestiges of tissue, wood cells, bark, spores, etc.

Most widely distributed are the decomposition products of organic life which have left no carbonized structural vestiges. These products consist

[457] Published by permission of the Director, United States Geological Survey.

of "humic" or "ulmic" or so-called "ulmo-humic" liquid products of decay. They may still be seen in aqueous solution in peats and other recent deposits, but in the Tertiary and older formations they are, for the most part, solidified. In general, these decomposition solutions are more or less filled with organic debris of minute to colloidal dimensions.

Most familiar among the carbonaceous sediments are the coals, carbonaceous clays, coaly shales, black shales, etc.; but the carbonaceous sediments also include disseminated or segregated organic matter in shales, clays, etc., in which the quantity of visible organic debris is in many cases insufficient to be readily detected without chemical or microscopical aid.

The carbonized debris and the organic decomposition derivatives formed during sedimentary deposition comprise the carbonaceous sediments of primary origin. In addition to these, there are products of secondary origin, derived from the primary by processes secondary or subsequent to their deposition. These include a great number of vagose hydrocarbon products, the most familiar of which are natural gases, petroleums, paraffins, asphalts, ozokerite, etc. The secondary group of carbonaceous products may or may not occur associated with the primary. They are usually disseminated, not only in the organic deposits in which they originated, but in any other porous beds into which they may have migrated. Solid hydrocarbon sediments of secondary origin also occur as dikes, veins, and as seepages at the surface.

Carbonized organic debris is more common in the finer grained aquatic deposits, especially clays and shales, which were laid down under conditions generally more favorable for the preservation of such debris. The material of primary origin in marine and lacustrine deposits is generally more or less distinctly "bituminous;" that in terrestrial swamp sediments is mostly "humic" ("ulmic") or coaly, whereas that in fluvial and pond deposits may contain both humic and "bituminous" matter. Mineral charcoal (fusain) is frequent in coals, sandstone, shales, conglomerates and agglomerates, sometimes in volcanic ash, and, rarely, in lavas.

The more abundant the carbonaceous matter, especially that in a solid state, the darker, in general, is the sediment. On the other hand, not all carbonaceous sediments are dark colored. Some, like the Tertiary oil shale at Marahu, Brazil, are a very light buff. Some of the oil rock at Platteville, Wisconsin, is light brown; other is brick-red, verging into chocolate color, thus resembling some of the very rich oil shale from Esthonia. Such cases, particularly when taken in connection with the observations of the U. S. Bureau of Soils,[458] indicate a much more widespread

[458] See U. S. Dept. Agriculture Bulls. 53, 1909; 74, 1910; and 80, 1911.

distribution of organic matter, mainly humic, in rocks and soils of different colors than has generally been suspected.

SOURCES OF ORGANIC SEDIMENTS

The surface of both land and sea is essentially covered with plant and animal life, the greater part of which is microscopical and of low organization. Season by season and generation by generation these organisms die, when they either serve as food for other animals and plants or mingle with the material in, on, or above which death occurs.

Control of Organic Sedimentation by Conditions of Supply and Deposition

Under ordinary conditions, when the animal or plant dies decomposition immediately sets in, beginning with the fluid contents of the soft tissues, and this decomposition, if unchecked, extends throughout and entirely consumes the organic remains. The survival of any part of an organism or of any secondary organic matter derived from it depends upon interference with the oxidation or decomposition processes.

Biochemical Decomposition

The common effective agents of destruction of all organisms not devoured as food by other animals and plants are (1) attrition and other means of mechanical disintegration; (2) fungi, especially moulds, whose work is saprophytic and so in part chemical as well as mechanical; and (3) bacteria and enzymes, the most far-reaching and all-important of which are the anaerobic bacteria. In genera and species suited to every type of organic debris, bacteria are present in essentially all natural environments in which a supply of oxygen adequate to their vital necessities is available. The anaerobic bacteria, living largely on the oxygen of the organic debris itself, represent the most enduring types and are able to function under the least favorable conditions.

When the processes of decay are retarded and finally arrested before the complete destruction of the animal and plant matter, the results are very different from the normal decomposition products, the most conspicuous distinction being the survival of some of the original organic compounds and the production of new ones. Mere retardation of decomposition may result in products such as CO_2, H_2S, marsh gas, and ammonia, but only ultimate suppression of the process of microbian (biochemical) decomposition at some stage has made possible the survival of solid organic matter in sediments.

Retardation and ultimate suspension of decay are caused, first, by the smothering of the oxidation processes by superposition of other kinds of

sediments, especially clays and silts, by deposition beneath stagnant water, or by a sufficiently rapid rate of accumulation of the organic debris itself; and, secondly and effectively, by the development of toxins through the action of the micro-organisms themselves, and their consequent self-poisoning; and, finally, by the less comprehensive and less important, though well known, effects of heat and cold.

The extent to which the dead plant or animal escapes decomposition, and the number of the surviving organic compounds and products, their chemical composition and their relative quantities depend on the kinds and amounts of original organisms contributed to the area of sedimentation, on the environmental conditions of their deposition, including especially the water conditions, and on the extent to which the decomposition processes go forward.

The relative scarcity of carbonaceous debris in some sandstones, its extreme rareness in eolian deposits, its more frequent occurrence in limestone and gray shale, and its abundance locally in clays and silts, are due in general to the relatively favorable conditions for preservation. Of these favorable conditions, the presence of quiescent, preferably stagnant, water in which the falling debris may accumulate is paramount, being in general hardly less important than excessive organic supply. Biochemical products and generated hydrocarbons are also gathered in aluminous and finely siliceous sediments by adsorption.

DEPOSITION OF COALS AND OTHER HUMIC SEDIMENTS

Environmental Conditions of Coal Deposition

The two main groups—"carbonaceous" and "bituminous"—of organic sediments generally differ more or less in their ingredient organic detritus, but the rather indefinite distinction between them is mainly the result of the difference in the environment of deposition. The so-called "bituminous" sediments—the bituminous shales, bogheads, cannels, etc.—are typically aquatic and, in most cases, are formed largely from aquatic organisms, including plankton that fall to the bottom as oozes or slimes—the so-called "sapropel." They are comparatively rich in hydrogen, particularly their secondary derivatives.

In contrast with the so-called bituminous deposits, the coal or coaly group is formed mainly from terrestrial land organisms—nearly all vegetable—laid down on land surfaces either very shallowly covered with fresh water, like some of the swamps of our middle Atlantic or southern states, or with a water level rising into the vegetable cover as in the familiar northern peat bog. Peats are embryonic coals. Therefore, whatever is known

of the formation and composition of peats and peaty deposits, such as peaty muds, applies to coals. The peats of most coals appear to have been deposited in coastal swamps and poorly drained areas.

The land floras composing the common coals consist mainly of carbohydrates and water, and, so, being relatively low in hydrogen, their deposits are less bituminous, strictly speaking, than most other organic sediments. They are truly carbonaceous sediments. They are characterized by the presence of much "humic," "ulmic," or "ulmo-humic" matter, on account of which they have been termed humic or humus coals.[459]

THE FLOOR OR UNDERCLAY. The bed of coal characteristically lies on detrital or sedimentary material, generally argillaceous, but sometimes sandy, or, more rarely, merely sand. This is the "underclay," sometimes called "fireclay," the Stigmaria clay of Paleozoic coal fields. In most cases its stratification is but slight or indistinct immediately beneath the organic deposit. It may be a few inches to several feet in thickness, and it may lie on rock of any type or origin.

The upper, unstratified part of the underclay is fine-grained, and generally it appears leached, as by subaerial exposure. In many places it has been more or less distinctly reworked, and it usually contains roots of subaerial vegetation, showing it to be an old soil.[460]

Not only are trees and other plants rooted in the underclays, but evidence of growth of the coal-forming vegetation in place is seen in the partings, on bedding planes, and in the roof of the coal beds. Near Madison, Missouri, the stumps of a forest of great trees stand silicified in place of growth in the underclay. In some of the younger coal beds of the western United States petrified stumps and roots are present *in situ* in the top of the coal.[461]

Locally the underclays bear evidence of partial erosion, and sometimes transported and water-worn trunks of trees with leaves, ferns, etc., are found buried in re-worked material. A Stigmaria or underclay is not always overlain by coal, but occasionally by shales or clays inclosing plant debris, or even by limestones.

Where the water was too deep for the rooting of land plants over a considerable area, their places were taken by aquatic vegetation and animals. and the deposits are of the sapropelic or more strictly bituminous type. Such deposits may fill a depression up to the point where vascular land plants could establish themselves.

[459] Cornet, J., La formation des charbons et des pétroles, Géologie, III, 1913. Les combustibles (charbon et pétroles), Ibid, 1920, 74 pp. Potonié, H., Entstehung der Steinkohle, 6th ed., 1920, pp. 24, 96.

[460] Stevenson, J. J., Interrelations of the fossil fuels, Proc. Am. Philos. Soc., vol. 55, 1916, pp. 21–302; vol. 56, 1917, pp. 53-151; vol. 57, 1918, pp. 1–48.

[461] See Potonié, H., Entstehung der Steinkohle, 6th ed., 1920, p. 118.

Occasional coaly deposits, for the formation of which the organic debris evidently was transported, or allochthonous, are found; these deposits, naturally, were not laid down on old soils. Such coals are nearly always very impure, variable in thickness, and of relatively slight horizontal extent.

EVIDENCE OF PLANTS AS TO OLD SOILS. The ecology of the coal floras has received little attention, possibly because it has long been taken for granted that coal was formed in the geological past under conditions prevailing in peat-forming areas of today. This assumption is true within certain limits, but the stratigraphic and depositional evidence in the important coal fields of the world shows that the coals were laid down in swamps on broad coastal or inland plains—lacustrine or fluvial—during stages of relative or approximate base level; that the regions were undergoing intermittently slow subsidence or, in the case of inland deposits, filling of the basins; and that the swamps were generally forested, similar to the coastal swamps of the southern United States, and more particularly in some tropical regions like Sumatra.[462] Prevailingly the soil in these swamps was overlain by a shallow, more or less stable covering of water, standing in general at the level of plant growth for a part, at least, of the year.

The plants of the coal beds show adaptations analogous to those of modern plants which flourish under the conditions postulated. The swollen or dilated basal portions of the trunks of *Sigillaria*, *Lepidodendron*, and some of the tree ferns; the air pores (pneumatophores) of the bark of the trunks, the shallow, wide-spreading roots; the development of new root stems and rhizomes at successive levels as in *Calamodendron*, *Annularia*, etc.;[463] thin-walled, lacunose tissue as in the cortical cylinders of the giant lycopods and tree ferns, provision for water storage as in *Sigillaria*, *Neuropteris*, etc., various pseudoxerophytic structures; the flotation air chambers of the Paleozoic fern-like higher plants; the heterosporous type of reproduction of many of the trees; the water resistant coverings of seeds, pollen, and spores; the absence of root hairs; the hollow interiors of Stigmarian appendages; air chambers in Calamarian roots; and the presence of Micorrhiza in the roots of *Calamites* for growth in a peat stratum, argue unmistakably for wetness of habitat.

The thickness of peat growth is largely determined by the stand of the water level, since the presence and composition of the latter regulate the rate of decay. The deposition of peat necessary to form a thick coal bed of the humic or ordinary type predicates a gradual rise of water to a height

[462] Potonié, H., Entstehung der Steinkohle, 6th ed., 1920, p., 188.

[463] Grand'Eury, F. C., Recherches géobotaniques sur les forêts et sols fossiles et sur la végétation et la flore houillères, 1re partie, 1re livre, 1912, pp. 1–49, pls. i-ix; 2me livre, 1913, pp. 50–116, pls. x-xx, 3me livre, 1914, pp. 121–173, pls. xxi-xxx. Potonié, H. op. cit., pp. 119–126, 172–181.

of possibly 100 feet in some cases, with maintenance during most of the time of depth such as to enable swamp plants adapted to the environment to grow in place. Rapid subsidence or failure of the water to rise terminates the further building up of the deposit. In the paralic (marine coast) deposits subsidence is shown by the invasion of salt water over the swamps where the land sank too rapidly. On the other hand, too rapid a rise of the fresh-water body drowned the land flora of the swamp, interrupting peat formation, and permitted the inwash of other sediments, largely inorganic. Subsidence is again conclusively shown by the renewal of coal formation on fresh-water soils at levels stratigraphically successively higher, and by the gradual transgression of the succeeding Coal Measures strata farther on the continent.

The great areas of many of the coal beds, such as the Lower Kittanning and Pittsburgh in the Appalachian trough, or the Raton bed in Colorado and New Mexico, and the remarkable geographic extent and relative regularity of the partings in the coals or of a given type of roof prove the great extent of the lowland swamps and their approximation to tide or lacustrine base level. As White[464] has pointed out, the water cover or zone of saturation may have been maintained over the surface of very gentle slopes by the dense growth and fall of the fecund vegetation itself, which, by its luxuriance, obstructed the run-off and held the water back to the point of overcoming this resistance either by too steep a gradient or by extermination of a part of the obstructing plant growth.

On a low and protected coast relatively free from tidal fluctuations, a very narrow halophytic zone—perhaps not more than a few miles or even one mile in width—forming a dense salt marsh belt, may well have sufficed effectively to oppose the invasion of water from the bordering shallow sea and its diffusion into the great fresh-water swamps, except at times of too rapid subsidence of the land or the breaching by storm or excessive tidal action of barrier beaches such as are characteristic of a subsiding coastal plain.

The Vegetable Contribution to Coal Formation. Without the aid of the microscope one who closely observes the bedding planes and edges of fragments of ordinary coal of any age can readily distinguish fragments of wood in the form of mineral charcoal. More careful search reveals impressions of bark, Stigmaria roots, stems, leaves (figs. 31 and 32), etc. One may also observe lumps of wound resin, the latter rare in Paleozoic but plentiful in many Mesozoic and most Tertiary coals.[465] The joint faces of

[464] White, David, U. S. Bur. Mines Bull. 38, 1913, pp. 53–64.

[465] White, D., Resins in Paleozoic coals, Prof. Paper 85, U. S. Geol. Surv., 1914, p. 65. See also Thiessen, R., Bull. 39, U. S. Bureau Mines, 1913, pp. 230, 273, 364.

Tertiary and Cretaceous coals, including even those evolved by alteration to the bituminous rank, show cross sections of branches, stems, and twigs appearing as glistening black lenses. The same features may be noted in

FIG. 31. BEDDING-PLANE CLEAVAGE SURFACE OF COAL OF MEDIUM BITUMINOUS RANK FROM WESTERN ILLINOIS, ABOUT 3 TIMES NATURAL SIZE

Shows fern pinnules and miscellaneous débris of land vegetation vertically compressed and cemented by colloidal groundmass. This layer of the coal bed contains much mother of coal (fusain). The fragment of wood on the lower right and the nerves of the fern pinnules are preserved as mother of coal.

FIG. 32. PHOTOGRAPH OF BEDDING PLANES OF HIGHLY LAMINATED BITUMINOUS COAL FROM INDIANA. ABOUT $\frac{4}{5}$ NATURAL SIZE

Shows promiscuous strewing of miscellaneous débris, consisting mainly of fragments of wood with which are mingled, however, fragments of ferns, bark, seedcoats, leaves, roots, etc., most of which are preserved as "mineral charcoal" (fusain). Splitting of the block shows the laminæ developed in great refinement and strewn with similar débris.

ordinary anthracites, whether Carboniferous (fig. 34) or Tertiary in age, and are to be seen in the graphitized coal of Rhode Island. In the less altered coals the woody matter is often so distinctly in evidence as to lead to the designation as "woody" of a coal already, for the same reason, bearing the name "lignite."

FIG. 33. FLAME-ETCHED, POLISHED SURFACE OF ANTHRACITE, AS SEEN UNDER THE METALLOGRAPHIC MICROSCOPE

The section, ground parallel to the bedding, cuts through a nest of large megaspores, probably belonging to *Lepidodendron* or *Sigillaria*. Photograph by Professor H. G. Turner.

A good hand lens brings into view much smaller material, and higher magnification reveals great numbers of spores, associated with minute resin particles and tissues of various types in which the details of the cells may appear. In anthracites it is difficult, without special treatment, to distinguish the plant remains, except in "mother of coal" in bedding planes in jet-like lenses and bands. By modern methods of treatment

up to a bituminous rank may be sectioned in the microtome or ground to a thinness of 5 to 8 microns so as to render them translucent, thus revealing their paleontologic and mechanical constitution.[466] The anatomical

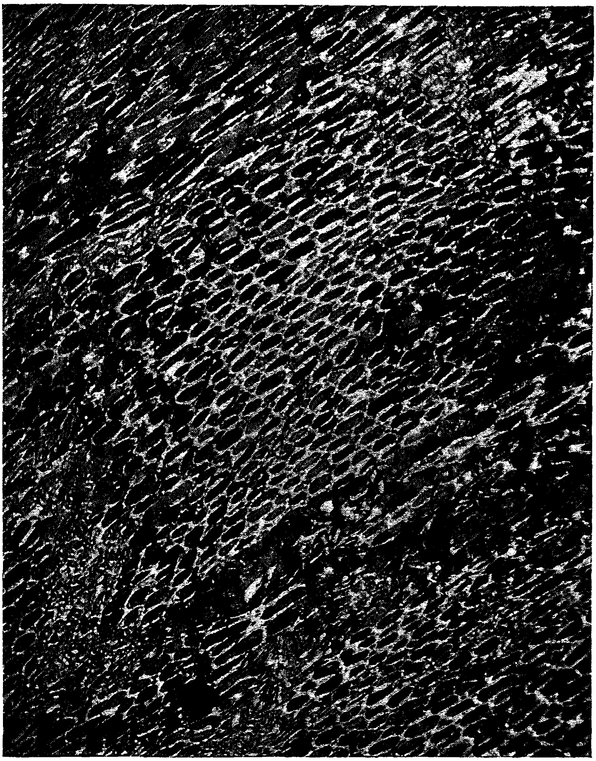

FIG. 34. FRAGMENT OF WOOD IN ANTHRACITE FROM THE MAMMOTH BED AT NANTACOKE, PENNSYLVANIA

Photograph by Professor H. G. Turner from flame-etched, polished surface under the metallographic microscope. The wood cells are cut obliquely in this specimen and preserved as "mineral charcoal" (fusain) in which many of the cells had been crushed as though brittle and fragile. A close inspection of anthracites shows mineral charcoal to have been common. About 80 times natural size.

features of the debris preserved in anthracite are admirably shown by viewing under the metallographic microscope surfaces that have been

[466] Thiessen, R., op. cit., pp. 206–302; Jeffrey, E. C., The anatomy of woody plants, 1917, pp. 444–469; Renault, B., Les micro-organismes des lignites, Compt. Rend., Acad. Sci., Paris, vol. 126, 1898, pp. 1828–1831; Sur la constitution des 'cannels', vol. 126, 1898, pp. 491–493; Sur quelques micro-organismes des combustibles fossiles, 1900; Renault, B., and Bertrand, C. E., Note sur la formation schisteuse et le boghead d'Autun, Bull. Soc. Indt. Miner., vol. 7, 1893, pp. 499–550; Thiessen, R., and White, D., The origin of coal, Bull.

slightly corroded by the blow-pipe or etching in selenium oxy-chloride,[467] or by Schultze solution[468] after polishing (figs. 33–34).

FIG. 35. PHOTOGRAPH OF A THIN SECTION THROUGH A "COAL BALL" TAKEN FROM THE COAL BED AT SHARNEY FORD, BACUP, LANCASHIRE, ENGLAND. ABOUT 1½ TIMES NATURAL SIZE

In this thin section of the nodule the vegetable débris, consisting mainly of the large petioles of fern-like plants (*Lyginodendron*) mingled with small and more delicate fragments of pinnules, etc., is preserved in unusual perfection, due to calcification which evidently occurred not far below the upper surface of the peat, which is seen to have been but little compressed at the time. It is not certain that biochemical decomposition had been completely arrested when petrifaction, in this case a very rapid process, took place, though the entire section is stained brownish by the humic decomposition products in which some of the small débris through the middle zone of the section seems to have been in partial suspense. The aggregate of débris here shown is typical of the matter composing the ordinary humic coal, though it is probable that decomposition proceeded farther in those portions of the peat outside of the segregations of calcite.

Both the composition of the plant associations and the conditions of the debris preserved in the fossil peat are shown in the greatest perfection in

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38, U. S. Bureau Mines, 1913; Jeffrey, E. C., Proc. Boston Society Nat. Hist., vol. 34, p. 333; Jeffrey, E. C., and Chrysler, M. A., The lignites of Brandon, Geol. Surv. Vermont, Rept. 1905, 1906, pp. 195–201; Jeffrey, E. C., Bot. Gazette, vol. 42, 1906, p. 1.

[467] Turner, H. G., and Randall, H. R., A preliminary report on the microscopy of anthracite coal, Jour. Geol., vol. 31, 1923, p. 306.

[468] Winter, H., Die mikroskopische Untersuchung der Kohle im ausfallenden Licht, Glückauf, Nr. 49, 1913, p. 1406.

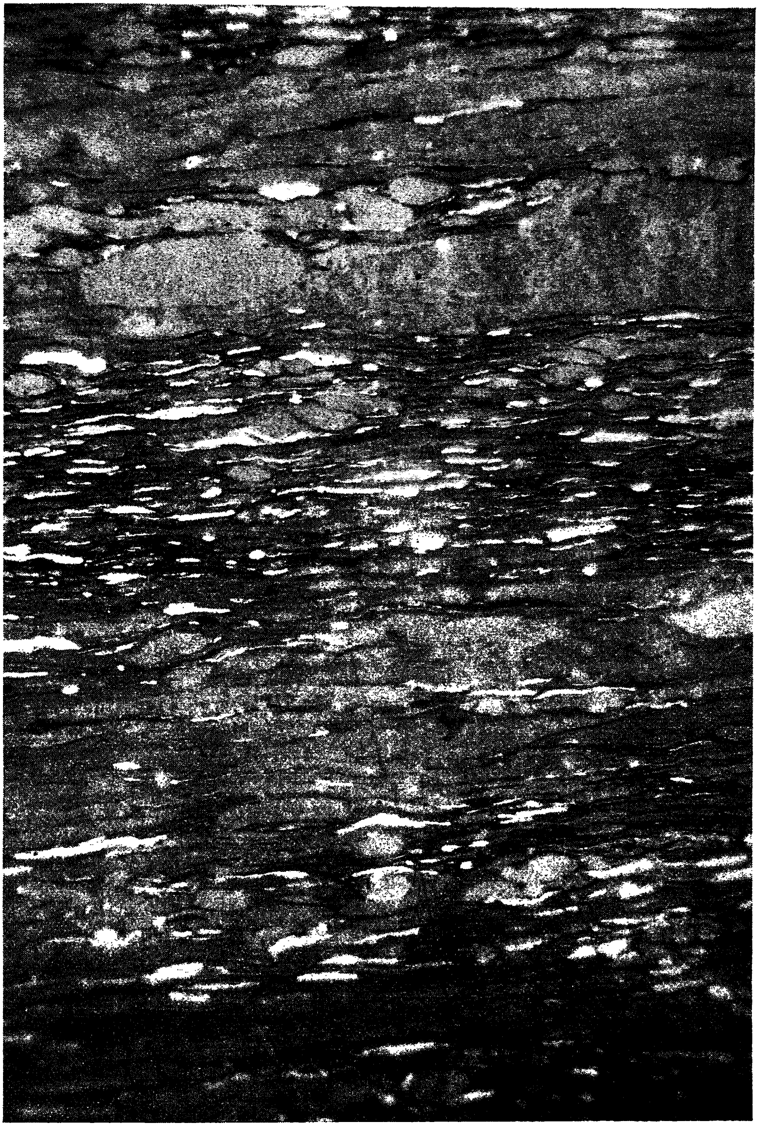

FIG. 36. VERTICAL SECTION OF COAL FROM THE BROOKEVILLE BED AT GROVE CITY, PENNSYLVANIA, 200 TIMES NATURAL SIZE

In this section the coal, composed largely of the remains of woody tissues, now flattened, embraces numerous lumps of resin of different sizes, now brought into closer relationship by the collapse and partial disappearance of the separating woody matter. A portion of a lenticular fragment of flattened wood, possibly "mother of coal," is shown dark mottled gray in the upper part on the right. Photograph kindly contributed by Doctor R. Thiessen.

the concretions sometimes found in coals and often slovenly designated "coal balls" (fig. 35). In many of the nodules a portion, at least, of the parenchymatous tissue was preserved in detail in the humic medium, now replaced by calcite or silica, all the structural details being admirably stained by the brown humic solution just as in so many of the petrified woods found in coaly deposits and black shales.[469]

Subject to some reservations, the general character of the plants or plant societies that have contributed to the formation of ordinary coals in different periods may be said to compare both in biological range and in chemical composition with the plant groups growing on the peat bogs of the present day. The relation is, however, closer by far with the peat-forming swamps of the temperate latitudes and even tropical regions, rather than the bogs in the regions of Pleistocene glaciation.

In the Carboniferous coals the botanical population in any area of a swamp appears to have varied somewhat from time to time according to the relations of the water level to the peat-forming surface, so that different coal beds and different parts of the same bed are made up of plant material of different adaptation and different type, the latter varying also with the geologic age. Many of the Cretaceous and Tertiary coals that are not too far altered contain an abundance of different kinds of wound resin which is largely due to concentration of resin contents by the decay of the enveloping wood cells, and in most coal of lower bituminous rank the aggregate volume of microscopic resin is vastly greater than that of resin seen by the naked eye. The Paleozoic plants were probably as rich in resinous, waxy, and fatty matters of different kinds as the plants in the coal-forming regions of the Cretaceous and Tertiary[470] (figs. 36 and 37).

Next to the evidence furnished by the coal itself under the microscope, the best testimony as to the composition of the peat-forming floras is to be

[469] Williamson, W. C., Philos. Trans., Roy. Soc., London, vol. 161, 1871, p. 477; vol. 162, 1872, pp. 197, 283; vol. 163, 1873, p. 377; vol. 164, 1874, p. 41; vol. 166, 1876, p. 1; vol. 167, 1877, p. 213; vol. 168, 1878, p. 319; vol. 171, 1880, p. 493; vol. 172, 1881, p. 283; vol. 174, 1883, p. 450; vol. 178B, 1877, p. 289; vol. 179B, 1888, p. 47; vol. 180B, 1889, pp. 155, 195; vol. 181B, 1890, p. 89; vol. 182B, 1891, p. 255; vol. 184B, 1893, p. 1; vol. 185B, 1895, p. 863; vol. 186B, p. 683; and vol. 187B, 1896, p. 703; Scott, D. H., Philos. Trans. Roy. Soc., London, vol. 189B, 1898, pp. 1, 83; vol. 191B, 1899, p. 81; vol. 194B, 1901, p. 291; vol. 198B, 1905, p. 17; vol. 205B, 1915, p. 313; Scott, D. H., and Jeffrey, E. C., Philos. Trans. Roy. Soc., London, vol. 205B, 1914, p. 315; Noé, A. C., A Paleozoic angiosperm, Jour. Geol., vol. 31, 1923, p. 344; Haskins, J. H., A Paleozoic angiosperm from an American coal ball, Bot. Gazette, vol. 75, 1923, p. 390; Kidston, R., and Lang, W. H., Old Red Sandstone plants showing structure from the Rhynie chert bed, Aberdeenshire, Trans. Roy. Soc. Edinburgh, vol. 52, 1920, p. 647; Horich, O., Über Analoga der Torfdolomite (coal balls) des Carbons in der rheinischen Braunkohle, Jahrb. k. preuss. geol. Landesanst., 31, Th. I, Hft. 1, pp. 38–44, Th. II, 1910.

[470] White, D., Resins in Paleozoic coals, Prof. Paper 85, U. S. Geol. Surv., 1914, p. 65.

found in the thin partings and, especially, in the bony layers and mineral charcoal (fusain) seams of the coal beds. A notable observation by paleobotanists is the great rarity of low herbaceous dicotyledons of terrestrial habits in the shales and clays of the Upper Cretaceous and Tertiary, though aquatic flowering plants, like *Trapa* and water lilies, may be present, as well as ferns in small numbers and variety, including swamp and lowland types.

CLIMATES OF THE COAL-FORMING PERIODS. Peat is now forming in the high latitudes, with and without excessive precipitation of moisture, and, locally, with really scant vegetation, the special effective cause being severe cold which effectively aids in arresting decomposition. Accumulation may be slow. Peat forms rapidly in regions of well distributed rainfall if the winters are not too severe, even though the mean temperature is never high, as in portions of Newfoundland and New Zealand. In tropical regions of low relief, peat is depositing where high temperature actually facilitates decomposition, but where lush plant growth furnishes abundant and even smothering supplies,[471] and heavy rainfall well spread throughout the year maintains high humidity and a relatively stable water cover[472] on the peat-forming area.

Much has been written on the climate of different geological periods.[473] Much of this is highly speculative, and some is more or less clearly erroneous.

[471] Regarding great plant growth in tropical swamps see Potonié, H., Entstehung der Steinkohle, 6th. ed., 1920, p. 155.

[472] The late C. A. Davis reported that in the United States peat was not forming where the annual rainfall was less than 20 inches.

[473] Carthaus, E., Die klimatischen Verhältnisse der geologischen Vorzeit vom Præcambrium bis zur Jetztzeit . . . Berlin, 1910; Peklo, J., Bemerkungen zur Ernahrungs-Physiologie einiger Halophyten, Oesterr. Botan. Zeitschr., vol. 62, 1912, pp. 172–179; Seward, A. C., Climate as tested by fossil plants, Quart. Jour., Roy. Meteorological Soc., vol. 40, no. 171, 1914, pp. 203–212; Nathorst, A. G., Sur la valeur des flores fossiles des regions arctiques comme preuve des climats géologiques, Compt. Rend., XI. Cong. Géol. Internat., 1910, pp. 743–755, and Ann. Rept. Smithsonian Inst. for 1911, 1912, pp. 335–344; Gothan, W., Die fossilen Holzreste von Spitzbergen, K. Svenska Vet.-Akad. Handl., vol. 45, 1910, p. 57; also Die Jahresringlösigkeit der palaeozoischen Bäumen und die Bedeutung des Klimas dieser Perioden, Naturw. Wochenschr., vol. 10, no. 28, 1911; Zalessky, M.D., Étude sur l'anatomie du Dadoxylon Tchinhatcheffi, Mém. Comité Géol., St. Pétersbourg, liv. 68, 1911, p. 21; and Études paléobotaniques, 1re partie, 1911, pp. 13–16, Appendix to part IV of the Bull. Soc. Natur. Orel, 1912, 25; White, D., Permo-Carboniferous climatic changes in South America, Jour. Geol., vol. 15, 1907, pp. 615–633; Gregory, J. W., Climatic variations, their extent and causes, Ann. Rept. Smithsonian Inst. for 1908, 1909, pp. 339–354; Bertrand, P., Les phenomènes glaciaires de l'époque permo-carbonifère, Ann. Soc. Géol. du Nord, vol. 138, 1909, pp. 92–125; Haug, E., Traité de géologie, vol. 2, 1911, pp. 822-829; Schuchert, C., Climates of geologic time, Ann. Rept. Smithsonian Inst. for 1914, 1915, pp. 277–311; Seward, A. C., Antarctic fossil plants, British Museum, 1914, pp. 25–29, 277–311; Knowlton, F. H., Plants as tests of climate, Bull. Geol. Soc. Am., vol. 32, 1921, pp. 353–358; Lemoine, P., Les glaciers de l'époque primaire, Revue scientifique, 27 juin, 1908.

The substance of White's[474] summary of the most salient environmental data so far as relates to climate is as follows: the Paleozoic, Mesozoic, and Tertiary coals were laid down in relatively flat regions of ample and preferably well distributed rainfall; the temperatures were relatively equable; the rankness and character of the vegetation, particularly that of the Paleozoic, show moderate warmth and moisture; the plants of the present living flora nearest related to the coal-forming types of the Paleozoic and older Mesozoic are now found predominantly in subtropical and tropical regions; the plant associations of the later Mesozoic and Tertiary basins indicate a mild, temperate, or subtropical climate and ample rainfall, although the well developed annual rings of the wood of the trees of these swamps in the temperate and subpolar regions show winter cold; widespread equability of climate is shown by the extensive distribution of similar or identical plant associations,[475] and the widespread heterospory in plants of the earlier Pennsylvanian coal fields, devices for seed flotation, and other adaptive characters show growth in swamps intermittently carpeted with water.

Available sunlight during even the earlier periods of coal formation is indicated by the development of palisade tissue, by the location of the stomata, and by other features of the leaf structure,[476] as well as by rate of growth.

Changes in Water Level and Drainage of the Coal-forming Swamp

Uniformity of deposition and character of the sediments throughout the thickness of a coal bed predicates stability of depth, composition of water, and continuity of character of the plant association, as well as of the organic volume contributed. It follows, that to avoid changes in an organic deposit, the water level must rise uniformly with the accumulation of the sediments. It is, however, observed in most cases that the structure of the coal beds shows that water level conditions were distinctly variable, which may have resulted from (a) erosional deepening of the outlets, with

[474] White, D., and Thiessen, R., Bull. 38, U. S. Bureau Mines, 1913, pp. 68–84.

[475] Coals and petrified trees were found by the Scott party at the 80th parallel in Antarctica. White has collected cycads, dicotyledons, and ferns over Cretaceous coals underlain by old soils as far north as the 68th parallel on the west coast of Greenland, while petrified trees are found in the Tertiary in the same region and northwest of Hudson Bay as far as the 82nd parallel. The cosmopolitan Jurassic flora has its representations in East Greenland, in Spitzbergen, in Nova Zembla, and in northern Alaska.

[476] Thomas, H. H., On the assimilating tissue of some Coal Measure plants, Proc. Cambridge Philos. Soc., vol. 15, 1910, pp. 413–415; On the leaves of Calamites, Philos. Trans. Roy, Soc., London, ser. B., vol. 202, 1911, pp. 80–83; Lignier, O., Bull. Soc. Bot. de France, vol. 63, 1915, p. 43; Seward, A. C. Fossil plants, vol. 3, p. 230; cf. also Rev. Gén. Bot., vol. 23, 1921, p. 689, pl. 34, figs. 2–5.

consequent lowering of the water level; (b) obstruction of escape through deformation of the region, through formation or enlargement of barrier bars, or through stream and current deposits damming back the swamp run-off; (c) rise of surface of the accumulating bed without corresponding rise of water level; (d) diversion of drainage to or from the area; and (e) climatic changes affecting the rate of plant growth, the run-off, or the evaporation.

The larger changes or "breaks" in the structure of the coal bed undoubtedly find their explanation as above. It is probable, however, that the minute lamination of the coal bed and its related deposits is due to seasonal changes and that it is connected with climatic phases of the year, in consequence of which, for example, the water level may shift, greater concentration of toxic products may be accomplished, the peat surface may be temporarily exposed, thin layers of fusain may be spread, or slight leaching of the surface may take place.[477]

Relations of Biochemical (Microbian) Decomposition to Water Medium and Rate of Organic Supply

On variable water conditions depend for the most part (a) the rate and progress of fermentation and decay of the organic debris before decomposition is arrested; and, concomitantly, (b) the generation and concentration of the toxic humic or ulmo-humic products which are important in causing the arrest of biochemical decomposition, and which play so important a part in the colloidal "ground mass" of the coal,—first as an aqueous solution of varying concentration and density, and, later, in the compressed and lithified deposit, as the solidified "binder" of the coal.

THE HUMIC DERIVATIVES. Given stagnation of the water cover at the surface of the growing peat deposit, the more rapid the concentration of the humic derivatives, the sooner is toxicity developed and decay arrested, and the less is the destructive consumption of the contributed ingredient organic debris. Rapidity of supply and accumulation of the organic debris facilitates the smothering of decomposition by excluding air or aerated waters, and conserves the toxic products, with consequent conservation of the raw material. Waste is greater with warmth of water and less with cold. Agitation of the water increases the supply of oxygen, whereas drainage or flushing causes loss of humic derivatives. Great acceleration of the supply of organic debris tends to offset waste by drainage; and if the debris accumulates sufficiently fast, the removal of the humic derivatives is interfered with, the toxic products are conserved, decomposition is arrested at very shallow

[477] White, David, Climatic implications of the Pennsylvanian flora: Bull. 60, Illinois Geol. Surv., Papers presented at the Quarter-Centennial Celebration, 1931, pp. 271–281.

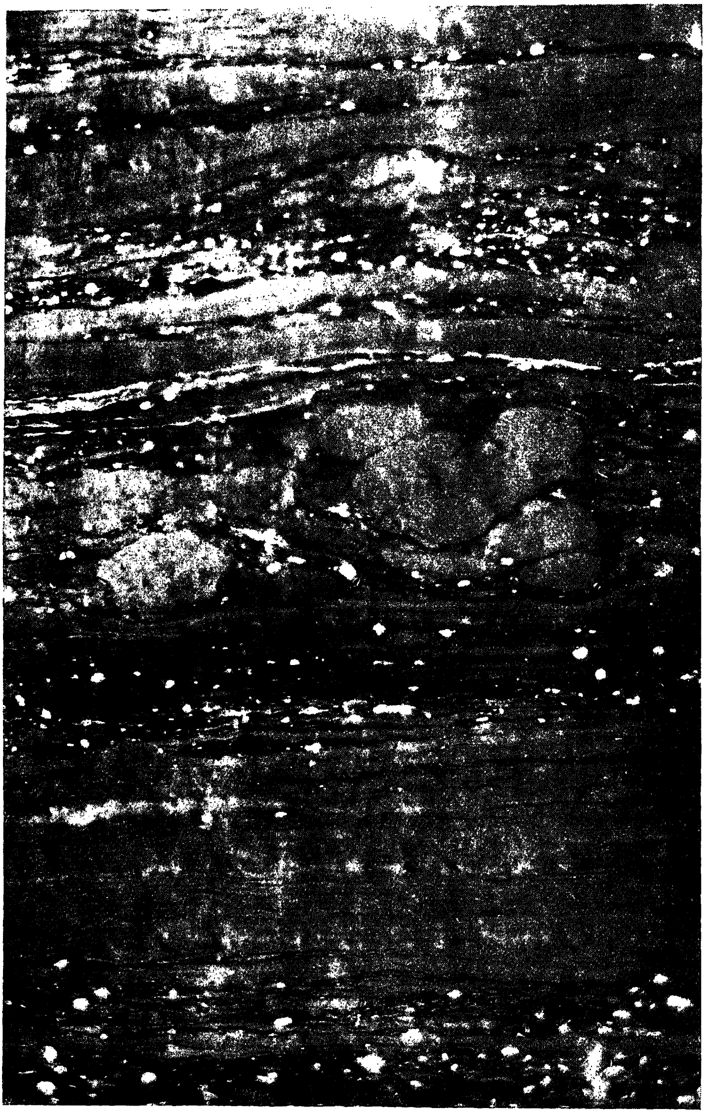

FIG. 37. VERTICAL SECTION OF FRAGMENT OF COAL FROM THE REDSTONE BED, BETTY MINE, MADISON, PENNSYLVANIA, 200 TIMES NATURAL SIZE

This photograph, contributed by Doctor R. Thiessen, shows more fully decayed material at the bottom, above which, and again near the upper part of the photograph, are bands of less completely decomposed woody matter. In the center of the photograph, in a zone of greater decomposition, are seen a number of lumps of resin freed and brought into contact by the disappearance of the surrounding tissues.

depths in the accumulating deposit, and larger portions of the raw material survive to be preserved (fig. 37).

The maximum depth at which anaërobic bacterial action may continue in a peat deposit is yet undetermined. It has been stated that bacteria spores in the resting stage and presumably capable of growing have been observed in a peat deposit at so great a depth as 30 feet.[478] It has even been claimed that bacteria have been found still alive in one of the Paleozoic bituminous coals of Germany, and in anthracite coal of Pennsylvania.[479] Corroboration is needed, however, as well as additional systematic observations.

Below the zone of bacterial activity the surviving organic debris is subject to no further biochemical decomposition. The process of peat formation is completed, and the plant matter then remaining continues its geochemical evolution, under dynamic influences, to coals of successively higher ranks.

Chemical decomposition, apart from microbian activity, probably takes place to some extent in certain cases, but its total effects in the sedimentary process are regarded as relatively negligible.

The humic derivatives in the typical coal-forming swamp are in general light brown to brown-black. They impart to the water the tea-color so commonly observed in the drainage. Several terms, including humin, ulmin, humic acid, ulmic acid, ulmo-humic acid, and carbo-humin, have been given to these substances.[480] Their composition and characteristics must vary considerably according to the ingredient raw material and the conditions of decomposition. They are imperfectly known, since the chemical investigation of the matter as it occurs in nature is complicated by the colloidal inclusions and conditions, the high molecular weights, and the insolubility of most of the substances in organic solvents.

Thiessen[481] reports the presence of two types or phases of humic derivative matter in some of the coals investigated by him: one a colloid embracing great quantities of cellulosic or ligno-cellulosic matter consisting of cell detritus, the other including similar minute debris resulting from the disintegration of spore and pollen exines, etc. The former is characterized by its carbohydrate matter, the latter by resinic waxy and oily or fatty debris.

[478] Thiessen, R., Bull. 38, U. S. Bureau Mines, 1913, p. 294.

[479] Fischer, Franz, Biology and coal: Proc. 3d Internat. Conference on Bituminous Coal, November 16–21, 1931, vol. 2, pp. 809–820. Lipman, C. B., Living microorganisms in ancient rocks: Jour. Bacteriology, vol. 22, pp. 183–198, 1931; also Fuel in Science & Practice, vol. 11, No. 5, pp. 164–171, May, 1932. Farrell, Michael A., and Turner, Homer G., Bacteria in anthracite coal: Jour. Bacteriology, vol. 23, No. 2, February, 1932.

[480] See Thiessen, R., op. cit., pp. 196, 227.

[481] Op. cit., p. 279.

The group of so-called humic acids, ulmic acids, humins, or ulmins are amorphous mixtures, largely the products of fermentation. Naturally, the aggregate varies according to the ingredient matter, the environmental conditions of deposition, which regulate the concentration of biochemical products as well as the extent to which the biochemical processes go forward, and especially the stage of carbonization of the coal. Further variation in the analyses depends on the method of preparation of the material. An average analysis approaches 63 per cent carbon, 5 per cent hydrogen, 32 per cent oxygen. The formulas calculated by different chemists also differ as widely as the analyses. The ulmins occurring in peaty and other sediments have been found to contain stearic and other acids, phytosterol, and cholesterol. They are reported by Bertholet and André as tribasic.

The presence, amounts, and qualities of the humins found in well known coals have received much attention from R. V. Wheeler, Wilfred Francis, and their associates in the Safety and Mines Research Board of the British Department of Fuel Technology. In their experiments they have attacked the various coals directly by alkaline solvents, such as sodium hydroxide, with or without the use of special oxidants, such as hydrogen peroxide or air at temperatures up to 150°C. In their classification all the extracted material is regarded as ulmins. The ulmins formed at times of deposition of the organic debris and readily soluble in alkaline solutions, are regarded as normal ulmins. "Ulmins" generated later in the deposits and insoluble in primary alkaline solutions, but which may be rendered soluble by oxidants, are termed "regenerated ulmins." Their molecular structure, which is changed geochemically in the process of carbonization, differs from that of the normal ulmins. The external groupings of the molecules are modified during oxidation, the more easily detached being eliminated to form simple oxygenated compounds with the substitution of carboxylic grouping, which renders the residue definitely acidic in character. The nuclear structure is described as built up by a compact system of benzenoid groupings connected together with heterocyclic structures, such as pyrole and furan and their derivatives.[482]

According to the definition and methods followed by the above mentioned investigators, "ulmins" comprise the greater part of the coals of high bituminous ranks, even to coking coals. In a banded coal of moderate bituminous rank the dull bands are found to yield 20 to 30 per cent of ulmins at 150° and 65 per cent at 200°, while the bright jetlike bands, the so-called vitrain, yield $95\frac{1}{2}$ per cent at 150°. The further the carbonization has progressed the less is the natural content of soluble humins and the less easily

[482] Jour. Chem., vol. 127, 1925, p. 2236.

can such humins be regenerated.[483] The principal source of the humins is the bright jetty layers, which enter nearly completely into solution, and the dull or attrital layers. The result is that a normal coal, visibly made up predominantly of branches, logs, stems, and plant detritus, is found to yield residues sometimes less than 15 per cent of the whole coal, which are classed as "plant entities."

By breaking down the nucleus of the molecule of the regenerated humins by dilute nitric acids (HNO_3 or H_2O_2), alipathic, dibasic acids were obtained having the properties of benzene polycarboxylic acids. They find oxalic, picric, succinic, and pyromellitic acids. The presence of the latter and the picric acids in the regenerated humins proves the presence of benzenoid rings in the matrix of a standard bituminous coal.

In the newly laid sediment the greatest concentration of the humic derivatives is naturally beneath the surface and within the peat itself, where they are less subject to aerating agitation, and where, at the depth of cessation of anaerobic action, their colloidal substance is gradually condensed by progressive dehydration under loading. Enrichment or leaching in the course of underground circulation is naturally possible.

The humic acids (humic derivatives) are low in hydrogen and high in carbon and oxygen. In some cases, as in dopplerite, they contain a small percentage of organic nitrogen, and possibly also a small amount of organic sulphur.[484]

Dopplerite is a dark substance which is essentially concentrated "humic acid" matter, with varying amounts of mineral matter, and it may have been formed by raising the zone of toxic concentration above the peat surface by evaporative reduction of the water body, and particularly where alkalinity has favored precipitation of the humic substances before the concentrate is filled with debris. The occurrence of spore exines or other minute debris in dopplerite indicates its colloidal nature. Such precipitation of humic matter probably has been relatively rare in the coal-forming swamps, yet the occurrence of some of the jetlike sheets broadly extending in the bedding planes, included by Stopes[485] under the term vitrain, may possibly represent such deposition.

Selective Order of Decomposition. Microbian action in effecting the decomposition of the organic debris is selective and progressive, and its order in a water medium proceeds from easily decomposable substances as

[483] Jour. Chem., 1928, p. 2969.

[484] Erickson, E. T., Manuscript; see also Odén, S., Die Huminsäusen, chemische, physikalische und bodenkündliche Forschungen, Kolloid-chemische Beihefte, Bd. 11, pp. 76–260.

[485] Stopes, M. C., On the four visible ingredients in banded bituminous coal. Proc. Roy. Soc., London, ser. B., vol. 90, 1919, pp. 480–487.

protoplasm and carbohydrates through more resistant substances as bark, gums, and cone scales to resinous and waxy materials.[486] Thus, a peat in which decomposition is quickly arrested, leaving much of the woody debris, would be vastly different from one in which biochemical decomposition has proceeded until very little of the carbohydrate substances remain, the body of the deposit being for the most part made up of resinous, waxy, fatty, or oily debris. It is thus seen that both the composition and the structure of the organic sediments, other factors being constant, are governed largely by the length to which biochemical decomposition proceeds before it is halted by toxins or smothering.

TYPES OF COAL AND THEIR DETERMINATION

The differentiation of coal into its various ranks is accomplished by geochemical and geophysical processes under dynamic influences, on account of which White has termed the general transformation of peat into coals of higher rank as "dynamochemical." The differentiation, however, of types of coal, is accomplished in the initial, or peat-forming stage of coal genesis.

To a certain extent the types are fixed, or at least influenced, by the kinds of organic matter contributed to the formation of the original peat. Local variations in the flora undoubtedly existed in different areas of the swamp at different times, with shifting of the floral elements according to changing conditions, all of which resulted in minor variations in the structure and composition. In some areas the raw material embraces much resin-bearing wood, plants unusually rich in waxes, herbaceous material, or large proportions of fatty matter and oils such as are furnished by certain flowering plants and by many algæ. The more marked differences in original material are mainly the result of modification of the environment, as by the presence of open-water areas or by estuarian relations, all of which lead to intergradation toward the distinctly aquatic or sapropelic type of deposit. The type of the coal and the structure of the coal are the products of the reactions of the environment, especially the water conditions, not only in determining the kinds of organic matter contributed but in controlling its deposition. These reactions determine very largely the nature of the deposit in the peat stage; they determine whether there shall be any coal deposited. Ferns, lycopods, and flowering plants in varying mixtures have taken part in all banded coal formations in all post-Devonian coal periods. So far as can be determined by structure or products, the composition of the plant substances composing algæ, Pteridophytes, Lepidophytes, Articulata,

[486] Thiessen, R., Bull. 38, U. S. Bureau Mines, 1913, pp. 227, 270, 285, 288.

and higher plants, consisting of carbohydrates, resins, fats, oils, waxes, cutins, pigments, and so forth, does not seem to have changed since late Devonian time. Chemically the ingredient plant matters are now essentially the same as in the early Tertiary, the Cretaceous, the Triassic, and the Carboniferous. Besides the paleontological and microscopical evidence, further proof of this is found in the close agreement between the analyses of the coals of different epochs, provided the samples compared are of the same rank.

There is great lack of international agreement either as to the nomenclature or the classification of coals. In fact the usage of every nation shows only too conspicuous incompatibility. Coals may be logically divided into two groups of types, the first banded, the second massive. The principal types composing these groups are based upon the predominance of some chief component, such as humified wood, mineral charcoal, and so forth.

In the following discussion a number of types will be roughly defined, with brief consideration of the chief components as they are now viewed by many American chemists and geologists.

(1) *Common, Banded, Striped, or Woody Coal*

This is the typical deposit of swamp origin in which the water level fluctuates, with consequent wide variance in stage of concentration of the toxic biochemical products. The depositional surface is subject to exposure at times. Accordingly, the vegetable supply is mainly, at least, carbohydrate land-plant material. Usually the coal is banded or striped in consequence of the preservation of the plant tissue, offering great detail at times of concentration of the water cover, while, due to aeration or exposure, decomposition may at other times have gone so far that only more resistant detritus, such as cuticles, spore exines, and so forth, are mingled with residual attrital debris. Variation in the water cover produces characteristic lamination and may permit the introduction of mineral charcoal. If the decomposition process ceases when the protoplasm, the sap, starches, proteins, sugars, and portions of the very soft and perishable tissues are broken down, the organic deposit, less water, will consist mainly of vascular debris —i.e., carbohydrates, principally ligno-celluloses—together, of course, with the more resistant material. This happens in a swamp with stagnant water cover in which a high concentration of toxic products permits comparatively little loss of organic material. A woody peat results which under pressure and other geodynamic influences eventually forms a woody or "humic" lignite or higher coal like the woody deposits in the Fort Union Eocene mined in Wilton, North Dakota[487] (fig. 38), of which Thiessen found

[487] See Thiessen, R., Bull. 38, U. S. Bureau Mines, 1914, p. 221.

wood to comprise over 80 per cent of the mass. The wood is usually more or less fully saturated with humic matter in solution, and the deposit is

FIG. 38. PHOTOGRAPH OF THIN SECTION CUT IN VERTICAL DIRECTION FROM LIGNITE OF FORT UNION AGE, AT WILTON, NORTH DAKOTA, 200 TIMES NATURAL SIZE

The photograph shows three bands in which the flattened wood cells, cut transversely, are clearly defined. The jagged oblique lines represent routes of the medullary areas now deformed by pressure of overlying strata. Wreckage of cells partly destroyed fills the intermediate zones. The irregular dark vermiform patterns, such as those seen in the upper macerated zones, correspond to contorted cells and canals filled with resin. Photograph by Doctor R. Thiessen.

generally more lustrous than other portions of the coal or other coal beds. This type includes the vitrainous or "glance" coals. Under most favorable conditions of humic concentration over the surface of the peat even the most delicate tissues are preserved.

(*a*) *Bright, humified, or vitrainous wood component* (*anthraxylon, vitrain, Glanzkohl, etc.*). Completeness of stagnation favors maximum conservation of the toxic solution, and such conditions seem to have been frequently approximated in the course of deposition of the coal-forming beds. Branches, trunks, and other material submerged in this fully toxic medium became saturated with humic products, with consequent generally remarkably complete preservation of cell structure. In this way are formed the lenses, streaks, or benches of *glance* or *bright* coal, which is characterized by abundance of humic matter, relatively excellent preservation of vegetable tissue,[488] and, naturally, by very low ash and the general absence of mineral charcoal. Zones of glance coal, therefore, predicate relative stagnation of the water cover.

When the bright glance or vitrified-appearing logs, branches, and so forth, occur in thick layers or pieces, these have been termed *vitrain*. Vitrain was supposed by the proponent, Dr. Stopes,[489] to be amorphous and to consist of ulmins similar to dopplerite containing little or no detrital matter. However, thorough examination of *vitrain*, including British specimens, by best microscopical methods, has in every case shown it to consist of wood or other plant tissues richly impregnated with ulmic matters. Wheeler and his associates were able to convert the entire mass of the glance or vitrainous woods into the so-called "regenerated humins," in consequence of which they reach the singular conclusion that the definite cell structure of the wood is pseudomorphic and is not to be included among the residues termed by them "plant entities." *Vitrain*, the bright jet-like wood, is therefore regarded as consisting practically entirely of "regenerated humins" or ulmins.

Bright or jet-like wood (anthraxylon of Thiessen, vitrain of Stopes) is practically always present in normal banded coals. When it predominates the coal may be termed bright, anthraxylous, or vitrainous.

Occasionally the layers or benches of dense jet-like wood, the so-called *vitrain*, are massive. In other cases the glance woody layers are thin and more or less distant, as in *clarain* (figs. 39–42). Often, however, the jet-

[488] Berry, E. W., Jour. N. Y. Bot. Garden, vol. 7, 1906, p. 5. Johns Hopkins Univ., Circular, no. 7, 1907, p. 89; Bull. Torrey Bot. Club, vol. 35, 1908, p. 249; Torreya, vol. 8, 1908, p. 233.

[489] Stopes, M. C., and Wheeler, R. V., Monograph on the constitution of coal, London, 1918.

like remains of stems and trunks are distinctly lenticular or even roundish. Layers of laminated coal with such lenses are more or less recurrently found in most coal beds of all ages, a fact showing their origin to be governed by conditions of deposition rather than by kinds of raw material. The jet of commerce consists of stem or trunk material similarly immersed or saturated with humic matter in a sapropel of a shallow Mesozoic sea.

(*b*) *Fusain, fusite, mineral charcoal, or mother of coal component.* Associated in varying amounts with the humified wood, sometimes intermingled

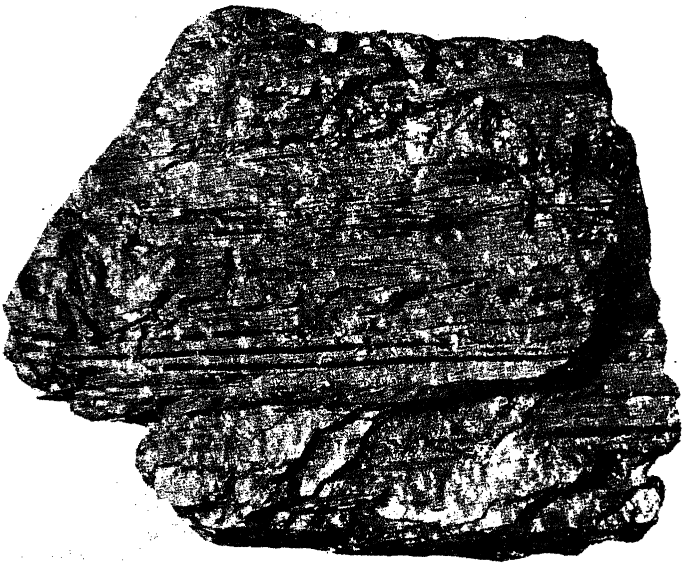

FIG. 39. LATERAL OR CROSS-SECTION VIEW OF FRAGMENT OF BITUMINOUS COAL FROM THE CRETACEOUS OF MONTANA, SHOWING DULL OR MAT LAMINATED MATERIAL, IN WHICH ARE EMBEDDED FRAGMENTS OF TRUNK AND BRANCHES PRESERVED AS BLACK JET-LIKE STREAKS AND LENSES. NATURAL SIZE

The bedding planes of this coal show miscellaneous d bris with "mother of coal" (mineral charcoal or fusain).

or even interlaminated with the latter, or at other times forming layers of considerable thickness in the banded coal, fusain or mineral charcoal is always present.

In most laminated coals there are to be seen layers, sometimes with greatest refinement of lamination, strewn with fragments of wood, bark, etc., often exquisitely preserved, which in structure, aspect, and friability resemble charcoal (fig. 43). Opinions vary as to the origin of this "mineral charcoal" or "mother of coal" (fusain), though most geologists and engineers

regard it as actual charcoal formed by fires[490] on the peat swamp, or in the forest from which it was washed out on the peat swamp. Against this conclusion may be noted: (1) the absence of ash beds and other evidence of burning; (2) the normal character of the peaty matter immediately below; (3) the development, great areal extent, and regularity of innumerable successive layers; (4) the impossibility of explaining the distribution and low inorganic content by transportation from dry land; (5) the fragility of

FIG. 40. LATERAL OR CROSS-SECTION VIEW OF BLOCK FROM COAL NO. 2, IN NORTHERN ILLINOIS. ABOUT NATURAL SIZE

The coal is highly laminated, consisting largely of débris including strips and fragments of bark, partially decomposed wood, twigs, etc., generally of dull aspect. In the upper middle portion of the photograph are shown three nearly parallel dark bands of black jet-like material, consisting of compressed wood, embedded in the laminated deposit. Each of these bands may represent a portion of a single log now greatly flattened. Thinner jet-like streaks are seen above the three bands. Short vertical shrinkage cracks cutting the jet-like layers are now filled with sulphates, probably of late origin, entering the bed by way of the joint systems. The coal shows much fusain on the bedding planes.

some of the preserved plant structures; (6) the rarity of real charcoal in peat; (7) the nature of the material itself.

[490] Stutzer, O., IN FUSIT, Vorkommen, Entstehung und praktische Bedeutung der Faserkohle—I, Ein kurzer Überblick über Eigenschaften, Vorkommen und Entstehung von Fusit, nebst Bemerkungen über Heukohle und Russkohle von Zwickau, Schrift. Gebiet Brennstoff-Geol., Freiburg, Hft. 2, 1929, pp. 1–22, text fig. 1–8.

FIG. 41. LATERAL VIEW, NATURAL SIZE, OF BLOCK OF COAL OF SUBBITUMINOUS RANK

Shows generally dull and laminated débris, the products of somewhat advanced decay of the organic matter, with cuticles and shreds of somewhat resistant structures (clairain) in which are mingled portions of branches and twigs of trees preserved in the humic decomposition concentrate and now appearing as irregular lenses of jet-like black matter in cross section. Coal of Laramie-Cretaceous age, from Marshall, Colorado.

FIG. 42. LATERAL VIEW OF FRAGMENT OF ANTHRACITE FROM PENNSYLVANIA, NATURAL SIZE

Consisting of laminated, more or less decomposed débris in which are embedded fragments of trunks, flattened and now preserved as vitreous jet-like lenticular layers, two of which are seen close together in the upper middle of the view; thinner lenticular streaks are in the lower half.

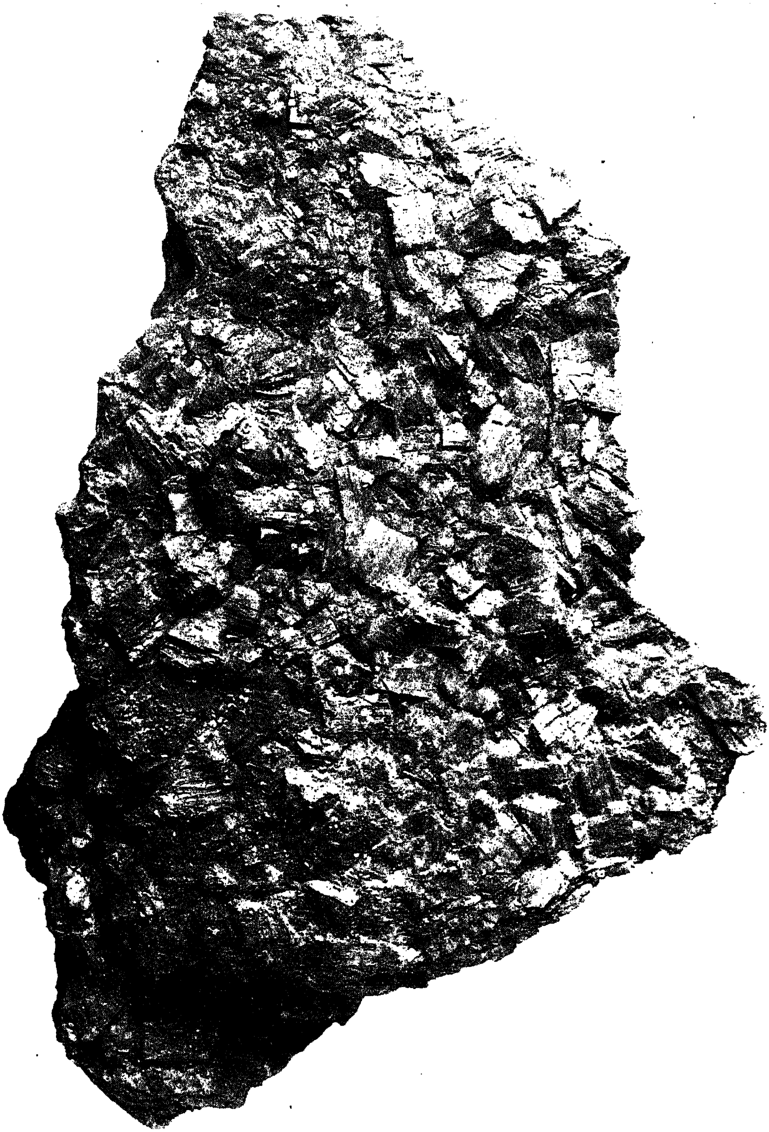

FIG. 43. "MOTHER OF COAL" (FUSAIN), ABOUT $\frac{4}{5}$ NATURAL SIZE

In this specimen the fragments have been moved from their original positions and redeposited, after slight rounding of some of the pieces, in all positions in a dark carbonaceous matrix, apparently composed of finely comminuted débris. The specimen is unique in the evidence presented of disturbance and redeposition of the carbonized fragments of wood.

The examination of layers and fragments of mineral charcoal in coal beds of all post-Devonian periods of coal formation points to the view that it represents woody debris lying in situ at the surface of the peat in the zone of biochemical decomposition at times of evaporation of the water cover, with consequent exposure of the peat. While the humic solutions were concentrating, the debris at the surface of the deposit was more or less impregnated by humic matter, and, on drying, very thinly incrusted therewith. The insolubility in water at ordinary temperatures of concentrated humic derivatives, when the matter has once been sufficiently dried, permits the belief that woody fragments, once soaked by the toxic concentrate, would, on drying in the air, be hardened and made resistant to further decay. They would not again be susceptible to attack by bacteria and would preserve their shape when again covered by the water medium and the peat-forming raw material in the process of decomposition.

Dominance of fusain characterizes the type as fusainous.

(c) *Groundmass, residuum, attritus, clarain of Stopes in part, durain.* Dilution, replacement, or notable fluctuation of the water medium, possibly temporary exposure of the peat surface, or reduction in the raw material supply prolongs or postpones the process of accumulation and concentration of the humic products and thereby permits decomposition to advance to the more resistant plant compositions, with the result, if this goes far enough, that the greater part or all of the woody or fibro-vascular (carbohydrate) material disappears, and only the still more resistant parts, such as cuticles, horny seed coats, etc., survive, together with minute and even submicroscopical cell detritus. These deposits are more or less distinctly granular and *mat.* These mat layers occur here and there in most coals while some coals are made up almost entirely of fine detrital material that is mat, especially on the edges. The minute plant refuse, some of which is ultra-microscopical in dimension, is termed attritus by Thiessen.[491]

Besides the attrital material in the groundmass the term is made by him to include exines of spores and pollen grains and microscopical algal colonies, all of which are not truly attrital. He does not include the aqueous humic compounds and other liquid products of biodecomposition which, now dehydrated and hardened, form an important part of the natural binder of the fuel. When the true attrital material is translucent it is included by Stopes[492] as part of clarain, her third principal component of British Paleo-

[491] Thiessen, R., Recently developed methods of research in the constitution of coal and their application to Illinois coals: Bull. 33, Cooperative Mining Ser. Symposium on Research Needs of Illinois' Coal Industry, Quarter-Centennial Celebration of Illinois State Geological Surv., 1930.

[492] Stopes, M. C., and Wheeler, R. V., Monograph on the constitution of coal, London, 1918.

zoic bituminous coals, the first two components being vitrain and fusain. Thin fragments of humified wood or anthraxylon are included by Stopes in her clarain, they being regarded as chemically and microscopically different from vitrain.

Due either to the presence of special original ingredient materials, which are opaque under the microscope, or to the fact that certain of the detrital material in the deposit becomes opaque at an early stage of carbonization, the truly attrital material in the groundmass of certain European and American Paleozoic coals of rather high bituminous rank is found to be more or less opaque. In the British specimens where this attrital matter is largely or wholly opaque, it was differentiated as a fourth component of British Paleozoic coals under the name durain. From durain, which Thiessen recognizes as opaque attritus, Stopes excludes as extraneous not only the exines and algal colonies, but resins and cuticles which are translucent (figs. 40–42).

Banded coals in which the groundmass or attrital material predominates have been termed mat coals or attrital coals.

A slightly massive or blocky coal of rather high bituminous rank, with fixed carbon approaching 60 or 61 per cent (pure coal basis), having sometimes a faintly grayish luster and rather coarsely granular fracture surface, and in which most of the attrital matter is opaque, has been differentiated by Thiessen as *splint coal*.[493] The opaque layers usually carry large numbers of saddle-shaped spore exines. These spores may have been produced by the particular plant responsible for the development of opacity at a relatively early stage of carbonization.

The Non-Banded, Massive Coals

(2) The *cannel* type, and (3) the *boghead* type

In depressions, ponds, or very sluggish or stagnant bayous in the coal-forming swamp, where too great depth of water prevents the growth of the subaerial swamp vegetation, and where the water is consequently open, the raw organic material of terrestrial origin is confined to such as falls in at the margin or drifts inward on water or wind. In these open areas aeration of the exposed water is somewhat greater, and thereby the decomposition of the supply of raw material is facilitated and may reach its subaqueous limit. Accordingly the woody and other vascular material generally disappears, leaving often little more than the most indestructible resins, waxes, and cuticles with disproportionately large contributions of wind- and water-borne spore and pollen exines (figs. 44 and 45). With these are

[493] Thiessen, R., op. cit., 1930.

mingled water organisms, both plant and animal, which take part by their decomposition in the development of toxicity and the production of humic

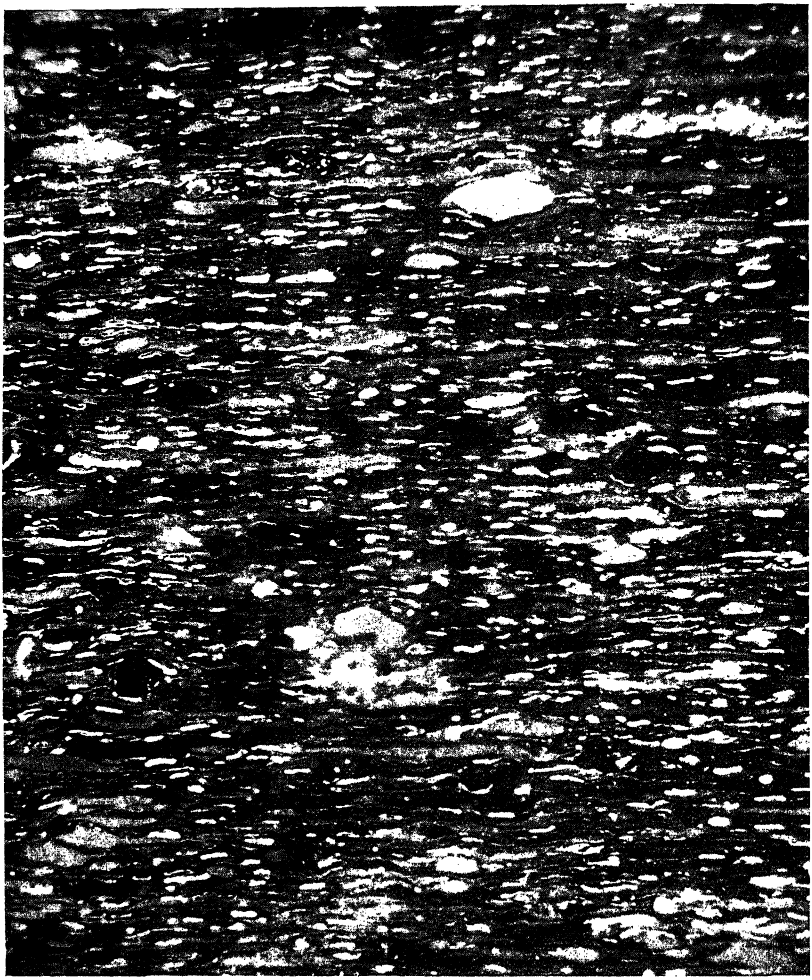

FIG. 44. VERTICAL SECTION OF CANNEL COAL FROM THE UPPER KITTANING BED AT NORTH WASHINGTON, PENNSYLVANIA, 200 TIMES NATURAL SIZE

This photograph, by Doctor R. Thiessen, illustrates a fatty stratum composed mainly of concentrated spore exines, showing as flatly lenticular bodies of somewhat irregular shape; resin lumps, some of which are large; and somewhat angular fragments or cuticle appearing as thin, irregular, somewhat thread-like horizontal elements of varying length, all embedded in the dark humic derivative groundmass, evidently derived largely from carbohydrate vascular plants which furnished the resins and produced the greater part, at least, of the spores.

substances, to which they give special qualities. Such deposits may contain varying, but always small, quantities of drifted woody debris. Due to the conditions of deposition the inorganic constituents are apt to be greater in relative quantity than in the adjacent swamps.

It is evident that the winding bayou or the small pond is likely to receive more infalling land vegetation than the large lake or lagoon, and that the

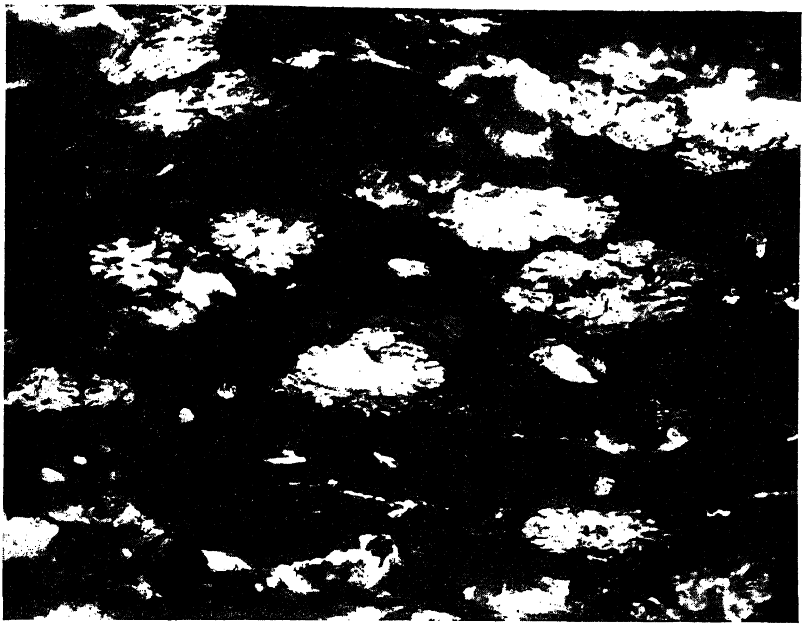

FIG. 45. THIN SECTION IN VERTICAL DIRECTION OF RICH LAYER OF CANNEL COAL FROM LESLEY, KENTUCKY, IN WHICH MANY MORE OR LESS DECOMPOSED ALGA COLONIES OF PILA KENTUCKYANA ARE ASSOCIATED WITH EXINES OF MEGASPORES, ALL APPARENTLY SUSPENDED IN THE HUMIC DECOMPOSITION COLLOID WHICH MUST HAVE BEEN OF GELATINOUS CONSISTENCY AT TIME OF IMMERSION OF THE ALGÆ, SPORE EXINES, ETC.

Magnified about 350 diameters. This layer of the Lesley cannel, which is of upper Pottsville age, and which forms an irregular but rather extensive lenticular mass, lying in the midst of a thick coal bed of the normal humic type, verges into the typical alga boghead, and, viewed by itself, might be appropriately classed with the oil shales and bogheads rather than with the cannels.

decomposition products of the latter are less largely derived from carbohydrate material. Fragments of cuticles are fewer and restricted to types more resistant; resin lumps are rarer; and the deposit consists more completely of spore and pollen exines enveloped in the humic ground mass. These deposits, when the ash or extraneous mineral sediments are not so great as to deprive them of fuel value, constitute the typical high grade

cannel or spore coals, including Fiminite and Tasmanite, shown by Jeffrey[494] to be a pure spore coal. "Cannel shale" and "bastard cannel" are terms applied to deposits containing such organic debris, mixed, however, with large proportions of inorganic sediments.

Algal and animal life play more prominent rôles when the water is broader or deeper; and, in the deposits consisting almost entirely of spores, we find larger proportions of the remains of algæ and fungi of compositions resistant to the agents of biochemical decay than in the pond or bayou. By reduction of the proportions of the exine contribution to correspond to broadening of the water, the proportions of algæ may increase, and the deposit, which is more distinctly aquatic, accordingly becomes more distinctly bituminous or sapropelic (fig. 45). Thus, we have, according to conditions of deposition, every degree of intergradation between the canneloid coal and the sapropel. There is no sharp line of distinction between mat or other laminated coals and cannels, but the name cannel is usually applied when little woody matter remains and spore material with resins forms by far the greater part of the mass.

Normally the surface of the cannel-forming deposit is not exposed to the air until filling of the water body has prepared it for growth of vascular plants. Nevertheless, the foliate or laminated weathering of many of these cannels seems to indicate seasonal variation in the deposition of these particular deposits and fluctuations in the rate of supply of organic debris.

Both in their environment of deposition and in their richly hydrogenous and low-oxygen composition, due to the resinous waxy and fatty-waxy exines and the higher fatty secretions in cuticles, etc., the cannel coals may be classed with the bituminous sediments rather than with the humic or coaly sediments. They are described in this place because the organic vestiges of the cannel are mainly derived from the terrestrial swamp flora, and because the colloidal humic derivative is so largely of terrestrial carbohydrate origin. Algæ are in evidence in many cannels, particularly those having least carbohydrate residues.

When the algal colonies predominate over the spore exines, the deposit, which is superficially similar to cannel in aspect, is known as an algal coal or boghead. As the algæ predominate more and more, the deposit is more highly hydrogenous and more distinctly bituminous.

Cannel and boghead coals occur in thin lenticular seams and in thick deposits. They are usually rather clearly demarked from the normal humic coal at top and bottom, but at the edges they verge at most localities into normal humic coal. Both are mat or dull or sometimes satiny; they are black

[494] Jeffrey, E. C., Econ. Geol. vol. 9, 1914, p. 735, pl. 20.

and brown; and when fresh they are massive or slabby, with conchoidal fracture surfaces; but they generally weather in thin laminæ.

Other Types and Phases of Coaly Deposits

The number of types and subtypes of coals and coaly deposits is undetermined. Among them are *semi-cannel*; *semi-splint*; *paper coal*; *leaf coal* or *cuticular coal*; *resin coal*; *pine needle coal*, etc. The classification, based on genetic features, may be carried to great detail. A few forms of coal, though not constituting true types, demand special consideration.

"Amorphous" Peat or Coal

Conditions of water and air may permit not only the decomposition and loss of apparently all the woody material, but, in fact, practically all of the readily visible detrital material, in which case the deposit has sometimes very inaccurately been referred to as "amorphous." However, no coal is really amorphous. Also such coals are usually more or less distinctly laminated. Through the amorphous or more thoroughly decomposed phases of coal the sequence passes into the ordinary carbonaceous and bituminous shales in which the organic matter is insufficient to give the deposit fuel value and so to bring it into a classification as coal.

The advanced, or nearly complete, elimination of the carbohydrate matter, as in the "mature" or "amorphous" peat, may bring into relative prominence (figs. 36 and 37) or even into overwhelming dominance the resin-waxy-fatty material, with corresponding change in the chemical character to the more hydrogenous composition of the deposit. "Amorphous" coals are usually relatively high in hydrogen, and, so, in heat value.

Laminated Coal

Deposits such as just described, but preserving considerable macerated and often shredded woody or integumental material, laid down in such sequence of extremely thin layers of slightly varied composition as to suggest seasonal fluctuations of the water level and concentration, form the typical laminated coal. Nearly all coals are more or less distinctly laminated. In general, mat coals show it most plainly, though lamination may appear in the course of weathering, even in massive coals like the cannels. "Mineral charcoal," internationally called *fusain*, may strew or cover the laminæ (fig. 39), or it may be scarce. Cleavage commonly is through the layers of "mineral charcoal."

Muck

Further evidence of temporary drainage and exposure of the peat surface is seen in the layers of muck occasionally found in the body of the coal, or even at the top of the bed. It is dull, brownish black, and sooty-granular or smutty in aspect, and sometimes somewhat powdery. In some cases this muck seems to have been reworked, with the introduction of stems and other material, in which case it has locally been termed "bone" and "rash."

Bone

Layers or benches of the coal may consist of stems, branches, trunks, etc., compressed and more or less well preserved in carbonaceous matter very high in ash, the composite suggesting an inwash of water carrying terrigenous sediment that gradually engulfed the growing vegetation.

The laminated "bony" carbonaceous material, with water-worn and drifted stems, that overlies coals No. 5 and No. 6 in large areas of central and southern Illinois, and which is present on the same coals of Indiana, is attributed to incursions of brackish or salt water over the fresh-water swamps, with consequent killing of the vegetation, interruption of peat formation, and some oxidation of the surface matter of the peat. The lamination of the deposit, with the occasional intercalation of very fine layers of white sand, was presumably produced under tidal salt marsh conditions, with corresponding periodic precipitation of the humic substances, a conclusion supported by the muck-like facies and sheeting of the carbonaceous matter and the occurrence here and there of calcareous layers with marine shells of a few species.

SUBMERGENCE OF THE PEAT

As has been noted, the submergence of the peat swamps by subsidence, or the too great rise of the water level, causes the elimination of a part or the whole of the plant growth, the greater oxidation of the water, the deterioration of the surface layer of the peat unless it is promptly protected by mud or other sediments, and, if there is simultaneous inwash of fine-grained sediments, the sealing of the deposit by clay or silt, and generally, the entombing of a part of the vegetation growing on or near the swamp at the time.

In fresh water the passage, with deepening water, from peat formation to clays or shales with much carbonaceous matter may be transitional; but wherever coal-forming swamps lie close above tide level, subsidence or the breaching of barriers may permit an incursion from the sea, in which case the terrestrial flora is expelled, and the surface peat is usually covered.

by partly oxidized or "brashy" matter high in ash, which probably represents or includes salt marsh deposits. Further deepening of the water over the swamp permits the invasion of inorganic sediments and the introduction of marine mollusca, as is seen to have taken place at so many points over several of the coal beds in southern Illinois, Missouri,[495] and Kansas. At those times are formed the concretions containing organisms, as nuclei, the "coal balls," and iron sulphide nodules.

The renewal of the process of coal formation in an area previously covered by the sea takes place only after expulsion of salt water and is caused by exclusion of the sea by barriers or by lifting of the land above tide level.

RATE OF ACCUMULATION OF PEAT

On account of the lack of accurate observations in sufficient number bearing upon the rate of accumulation of peat, opinions on this subject are widely variant. Further, the examination both of peats and coals shows that the rate must have fluctuated greatly, that of a woody deposit laid down under favorable conditions being necessarily very much greater than that of a so-called "amorphous" or attrital stratum composed for the most part of residual particles of resin, spore and pollen exines, morsels of cuticle, etc. In the glaciated regions records point to a maximum accumulation of 1 foot in 10 years at the surface, which is equivalent to perhaps not more than 4 or 5 inches of peat at a depth of 20 or 25 feet, if the peat is moderately fibrous. No records relate to environments permitting only very slow accumulation. Probably an estimate of a rate of accumulation of 1 foot in 75 years at a depth of 25 feet from the surface is a fairly conservative average, since at this depth a portion, perhaps 35 per cent, of the 80 per cent or more of water which composed the top layers of peat, will have been expelled under loading.[496] One foot of dense hard peat might, under favorable conditions, be laid down in 100 years.

It is, on the other hand, reasonable to assume that during the periods of extensive coal formation when climatic and growth conditions were far more favorable than now in the northern regions, the accumulation of distinctly woody peat was much more rapid; and it seems not improbable that peat like that from which the lignite at Wilton, North Dakota, was developed, might, during the more favorable intervals, have accumulated at a rate perhaps greater than 1 foot in 50 to 75 years.

Consideration of the reduction of peat in the course of its geochemical

[495] Hinds, H., and Greene, F. C., The stratigraphy of the Pennsylvanian series in Missouri, Rept. Missouri Bureau Mines and Geol., vol 13, 1915.

[496] See Smith, R. A., in Mem. Lit. and Philos. Soc. Manchester, vol. 25, 1876, p. 281; Jones, T. R., Proc. Geologists' Assoc., vol. 6, 1880, p. 207.

evolution, under dynamic influences, to lignite, bituminous, anthracite, and graphite coals is fraught with possibilities of multiplication of the initial error.[497] In any calculation of the thickness of peat represented by a foot of bituminous coal or anthracite, account must be taken not only of the tremendous vertical compression of the deposit under great thickness of superposed strata and under thrusts in regions of alteration to high bituminous or anthracite ranks, but also of the losses of oxygen, carbon, nitrogen, and hydrogen in the form of gases and volatile hydrocarbons which are to be added to the progressive losses of water which, in the anthracite, is reduced to about 3 per cent. The 25 per cent or more of oxygen in the organic matter of the upper layers of peat is in anthracite reduced to 3 per cent or less, and 5 or 6 per cent of hydrogen to about 2 per cent. Estimates of the real losses of carbon and hydrogen on the way from peat to anthracite are subject to great error.

The conclusions by Renault,[498] based upon the observation of coalified stems of bituminous rank found embedded in the shales, that the stems have been reduced to one-seventeenth or perhaps one-twentieth of their original volume, and that the different vegetable tissues have lost $\frac{11}{12}$ to $\frac{29}{30}$ of their original volume, though interesting as showing the loss in a single trunk or plant stem under conditions favorable for its preservation, take no account of the waste of raw material in the development of the ground mass (the humic acid substances), or the loss of the latter, and so of indeterminate amounts of raw material, by flushing before the water is brought to the stage of humic concentration necessary for the survival of the particular stem.

Ashley[499] estimated the time required for the deposition of the Pittsburgh bed in southwestern Pennsylvania at about 2100 years, which is not far from that given by Lesquereux.[500] These estimates probably understate the length of time required for such a coal as the Pittsburgh bed.

THE ASH OF COALS

The inorganic mineral sediments in peats and coals are derived from the raw organic debris itself, from material in suspension or solution in swamp waters, or from dust deposited by the atmosphere, the relative contribution varying with the environment. Due to leaching and substitution it seems

[497] White, D., Bull. 38, U. S. Bureau Mines, 1913, p. 85.

[498] Renault, B., Micro-organismes des combustibles fossiles, 1900, p. 440.

[499] Ashley, G. H., The maximum rate of deposition of coal, Econ. Geol., vol. 2, 1907, pp. 34–37.

[500] Lesquereux, L., The vegetable origin of coal, 2nd. Geol. Surv. Pennsylvania, Ann. Rept., 1885, p. 113.

probable that a coal having 6 per cent or more of ash reflects in the composition of the latter the mineralogy of the environment or substratum of the bed. However, it is reasonable to assume that when the ash does not comprise more than $3\frac{1}{2}$ per cent, it has its origin, mainly, at least, in the large number of calcium, silica, iron, potash, sodium, and phosphate compounds originally taking part in the plant organism.

As the result of the analyses of separate portions of a bed Lessing[501] finds that the average percentages of ash found in a number of samples were as follows: *fusain*, 15.59; *durain*, 6.26; *clarain* (which consists partly of *vitrain* and partly of *durain*, with some *fusain*), 1.22; *vitrain*, 1.11.

Fieldner, Hall, and Feild,[502] of the United States Bureau of Mines, after reviewing the composition of coal ash, report that the analyses of the ash of most coals fall within the following limits:

Typical limits of ash analyses

Constituent	*per cent*
SiO_2	40 to 60
Al_2O_3	20 to 35
Fe_2O_3	5 to 25
CaO	1 to 15
MgO	0.5 to 4
$Na_2O + K_2O$	1 to 4

DEPOSITION OF SAPROPELIC BITUMINOUS SEDIMENTS

Sapropel

The bituminous equivalents of peat and peaty or coaly deposits consist, according to the conditions of deposition and the nature of the ingredient material, of organic muds, slimes, or oozes, to which Potonié[503] gave the name *sapropel.* Like the humic deposits, the sapropels vary from inorganic sediments containing decomposition products with occasional very resistant debris of organic origin, to deposits laid down under conditions of abundant raw material supply in water sufficiently toxic to permit the survival of large amounts of the ingredient material including much that is structurally delicate.

Environmental Conditions

In the sapropelic group, which includes the bituminous shales and limestones, oil shales, bogheads, etc., the raw material contributed to the proc-

[501] Lessing, R., Jour. Chem. Soc., vols. 107–108, pt. 241.

[502] Fieldner, A. C., Hall, A. E., and Feild, A. L., The fusibility of coal ash and the determining of the softening temperature, Bull. 129, U. S. Bureau Mines, 1918, pp. 13, 27; see also Selvig, W. A., and Fieldner, A. C., Fusibility of ash from coals in the United States, Bull. 209, U. S. Bureau Mines, 1922.

[503] Potonié, H., Sitz. Gesell. Naturf. Freunde zu Berlin, 13 Dec., 1904; Jahrb. k. Preuss. Geol. Landesanst. u. Bergak., vol. 25, 1904, p. 342.

esses of organic sedimentation embraces minor portions only of terrestrial plant life. It is for the most part laid down in ponds, lakes, lagoons, inland seas, and shallow gulfs too deep for vascular plant growth in place, too extensive to permit a considerable contribution of detritus of land origin, and sufficiently protected against tidal scour and aerating currents to favor the necessary degree of conservation of humic products.

In the bituminous shale-forming lagoon, as in the coal swamp, the conservation both of raw material and decomposition products increases with the degree of stagnation and with the rate of supply and the kind of the material. Inevitably changes in the indigenous fauna and flora result from changes in the stagnant and more or less acid zones of the water. Molluscan life, for example, is strongly affected and greatly reduced in variety, if not in size. In the less protected areas only the most resistant material, such as resinous substances, waxes, chitins, and other organic debris of especially resistant composition escapes decay, along with the hard parts of animals. On the other hand, in the most favorable environments, delicate tissues such as fungi, moulds, and filamentous and unicellular algæ may swarm in the toxic decomposition concentrate.

Ingredient Organic Debris

The plant material of the raw supply contributed to the aquatic or open water regions of organic deposition consists mainly of sea weeds (algæ), diatoms,[504] fungi, bacteria with wind-blown pollen and spores, and generally a small land element contributed by current drift.

The animal matter, though naturally in far less volume than the plant matter, is nevertheless, enormous in the aggregate, and many types are represented. The principal animal debris of organic composition is coprolitic, and this is sometimes abundant. Soft parts have not been recognized under the microscope, but they are reasonably believed to have contributed to the aggregate of biochemical products that may have been retained in the groundmass or binder of the rock. The various fatty acids contributed by them will not in general differ appreciably from those contributed by the fatty plants, especially unicellular algæ.

Decomposition and Decomposition Products

The waters of bituminous shale deposits are to be thought of as generally teeming with life; they may be warm or cold, fresh, alkaline, or strongly saline. Sapropelic deposits rich in organic matter are found in the semi-

[504] For the protein and fat contents of diatoms, see Bode, C., Festsch. Naturf. Gesell. zu Emden, 1915.

stagnant saline depths of the Black Sea,[505] in the shallow estuaries of the Baltic,[506] in and about the saline lakes of Turkestan, southeast Africa, and southwest Australia,[507] and in the playas of Nevada. Concerning the selective action of the micro-organisms and the qualities of the various deposits characteristic of the different waters, little information appears to be available, and there is great need of systematic and detailed field observations.

As to the order of decomposition of aquatic life in lake, estuary, and sea, it appears that plant protoplasm, and in most cases the gelatinous and mucous substances which are less resistant to bacterial decomposition, quickly disintegrate, and later the cellulosic matter of the original cell membranes, whereas the waxy and waxy fat or "higher fat" products, the resinous exines, and the chitins are last to be lost.

Sapropel deposits have been described and illustrated by Potonié[508] and analyses of typical sapropelic sediments have been given by Stremme[509] and Späte.[510] Many hundreds of bottom sediments, gathered from a wide range of environments in different regions, have been examined by Parker D. Trask[511] in connection with a study of the sedimentation of possible mother rocks of petroleum, the researches being conducted under the auspices of the Research Trustees of the American Petroleum Institute. Trask finds no "liquid hydrocarbons" in any sample yet examined, the conclusion being that petroleum is neither present nor produced in the sediments at time of deposition. It may be noted that the conditions of occurrence of most of the recent sapropelic deposits that have been analyzed do not seem to assure the cessation of biochemical action in the sample analyzed. Analyses have also been made of fossil sapropelic deposits (sapropelites) of different periods, and they have been microscopically described by several paleontologists.[512]

[505] Andrussow, N., Guide des excursions, 7. Cong. Géol. Internat., no. 27; also Clarke, J. M., Mem. 6, New York State Mus., pt. ii, 1903, p. 199.

[506] Twenhofel, W. H., Notes on black shale in the making, Am. Jour. Sci., vol. 40, 1915, p. 272; see also Wahl, E. von, and Kupfer, K. H., Baltische Landeskunde, 1911, p. 242.

[507] See Hoefer, H., Das Erdöl, 4th ed., 1922, p. 261.

[508] Potonié, H., Die Entstehung der Steinkohle und der Kaustobiolithe überhaupt, 6th ed., 1922, pp. 26–34.

[509] Stremme, H., Das Erdöl und seine Entstehung, Vortragstoffe für Volks Familienabende, H. 21, 1907.

[510] Späte, F., Die Bituminierung. Ein Beitrag zur Chemie der Faulschlammgesteine. Inaugural-dissertation zur Erlangung der Doktorwurde genehmight von der Philosophischen Fakultät der Friedrich-Wilhelms-Universität zu Berlin, Aug. 10, 1907.

[511] Trask, P. D., and Wu, C. C., Does petroleum form in sediments at time of deposition? Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 1451, 1463.

[512] Bertrand, C. E., Bull. Soc. Ind. Minér., vol. 6, 1892, p. 453; Bull. Soc. Belg. Paléont. Hyd., vol. 7, 1893, p. 45; vol. 11, 1898, p. 204; Bull. Soc. Hist. Nat. Autun, vol. 9, 1896,

Carbonized remains of algæ visible to the unaided eye are, in general, not rare in fine-grained deposits. They are found in black shales and are far from uncommon in bituminous limestones; they are rarest in coarse sandstones and white crystalline limestones. In an environment where the supply is rich and the toxic products are conserved, the losses of raw matter are least, and even very delicate structures, including the carbohydrate cell laminæ of algæ and fungi, may escape decay.[513] In such an environment the preservation of plants like algæ is sometimes extraordinarily striking. From this optimum downward, gradation in the bituminous matter proceeds stage by stage to deposits composed of only the most resistant vestiges in a matrix of inorganic substances laid down in water charged with decomposition products. In some cases the decomposition solution gives the shale a dark color, where only occasional spores or other debris are revealed in thin section under the microscope. Such deposits appear to result from a close balance between raw material supply and biochemical decomposition. Where indestructible vestiges are rare, the assumption that the supply was meager appears justified. The results vary, of course, with the inorganic matter deposited with the organic.

The view that the colonial one-celled algæ of the *Pila* and *Reinschia* type are spore exines, as held by Jeffrey,[514] or that in general they, together with the generally recognized spore exines, like *Sporangites* and *Tasmanites*, are mere agglomerations of bitumen (Bitumenzusammenballungen), as has recently been proposed by a German investigator,[515] has been completely disproved, Thiessen having demonstrated beyond doubt the algal nature of *Pila* and *Reinschia* in connection with his studies of recent Coorongite. Both the algal nature of the genera last named and the spore exine structure of *Tasmanites* and other exines common in cannels and in oil shales have been indisputably proved by T. Stadnichenko[516] through the observation of the structural details revealed by the spore exines when heated in a microfurnace.

It is well known in general that animal tissues are attacked by the mi-

193; Bull. Soc. Ind. Minér., vol. 11, 1897, p. 551; Trans. et Mém. Univ. Lille, vol. 6, no. 21, 1898; Ann. Soc. Géol. Nord., vol. 28, 1899, pp. 267, 171; vol. 29, 1900, p. 25; 8. Cong. Géol. Internat., Compt. Rend., 1901, p. 159; 1. Cong. Internat., Mines, Compt. Rend., 1905, p. 349; Bull. Soc. Hist. Nat. Autun, vol. 26, 1913, p. 337.

[513] White, David, and Stadnichenko, T., Some mother plants of petroleum in the Devonian black shales, Econ. Geol., vol. 18, 1923, pp. 238–252.

[514] Jeffrey, E. C., On the nature of some supposed algal or boghead coals, Rhodora, vol. 9, 1909, pp. 61–63; The nature of some supposed algal coals, Proc. Am. Acad. Arts and Sci., vol. 46, 1910, pp. 273–290.

[515] Potonié, Einführung in die allgemeine Kohlenpetrographie, Berlin, 1924, p. 135.

[516] Stadnichenko, T., Annual report to American Petroleum Institute on research project No. 3 (Studies of source rocks in the microfurnace), 1928. (Unpublished.)

crobian agents of decomposition much more promptly and effectively than are plants, and that the tissues of the soft parts of animals disappear much more quickly than do even the delicate plant structures. Thus, while the skeletal animal parts, largely of inorganic composition, may continue beyond the peat stage and into advanced regional alteration, the preservation of recognizable tissues of soft parts in marine or lacustrine sediments is so rare that few such discoveries have ever yet been made. Richly bituminous shales carrying abundant shells, fish scales, and excrementa of animals, etc., are found to contain enormous quantities of delicate plant debris, but no record of soft animal tissue.

The probable survival of insect eggs into the peat stage and their silicification in advance of appreciable compression is shown by the discovery by Renault,[517] and of possibly far greater significance is the description by Gümbel[518] of matter regarded by him as fat obtained in a single dredging at a depth of 5103 meters in Latitude 42°9,3′, Longitude 14° 38, 2′, about 5° west of the Spanish coast. The dredging contained small nodules of a very light white substance intimately distributed through clay. The substance does not wet easily, melts in boiling alcohol, though hardly soluble in cold alcohol, and separates on cooling or mixing with water. More conclusive evidence as to the real nature of this material, particularly its chemical character, is greatly to be desired.

It is therefore to be assumed, tentatively at least, that whereas fatty, waxy, and resinous, or even less resistant plant substances may be preserved in the vegetable debris of the sapropel, the shale, and the limestone, all qualities and effects resulting from the animal soft parts of the raw material contribution to the deposit reside only in the decomposition derivatives in the humic solution. In other words, the effects of the animal contributions to the organic deposits are essentially indirect. Preservation of the soft parts of animals is so extremely rare as to be negligible as source of hydrocarbons in oil or coal fields.

The theory of the origin of petroleum from animal fats and oils[519] is predicated on the preservation of the fatty animal matter or fatty acids of animal origin in the deposits through the peat stage and on beyond into the sphere of subsequent dynamochemical action. The study of the fossil sapropelic deposits has not yet lent tangible encouragement to the view that animals more than plants have served as sources of petroleum in our oil

[517] Renault, B., Sur quelques micro-organismes des combustibles fossiles, 1900, p. 410.

[518] Gümbel, G. W. von, Die mineralogisch-geologische Beschaffenheit der auf der Forschungsreise S. M. S. "Gazelle" gesammelten Meeresgrund-Ablagerungen, Die Forschungsreise S. M. S. "Gazelle" 1874 bis 1876. Theil II, Physik und Chemie, 1888, p. 69.

[519] Hoefer, H., Das Erdöl, 4th ed., 1922.

fields. It would seem that only under conditions so exceptional as to be little short of cataclysmic, which would cause simultaneous and exceptionally abrupt killing of the animal population with coincident accumulation and deep burial of the dead matter, can soft parts of the animals be preserved in accordance with the requirements of the animal theory.

The products of the total biochemical decomposition of the animal tissue may form part of the colloidal ground-mass solution, and the decomposition derivatives, mingling with those of the plants, may contribute new compounds and impart new qualities to the humic aggregate, thus making the derivative solution more distinctly bituminous.

It is the belief of E. T. Erickson that a certain degree of preservation of animal tissue may take place in a sufficiently toxic colloidal solution containing humic acid. He points out the possibility that animal tissue under these circumstances will slowly yield to an extent to chemical degradation by hydrolysis, in which the acidity or alkalinity of the containing water may be a factor. The amino acids largely yielded by proteins as final chemical degradation products are characterized by chemical reactivity in which they are known to take part in the formation of humic acids. In the toxic humic colloidal solution, fatty material may also undergo chemical degradation by hydrolysis into certain saturated and unsaturated, generally higher, organic acids and free glycerine.

Erickson believes that the toxic colloidal solution accordingly affords a means whereby its simpler chemical degradation products, if not the animal tissue itself, may be preserved beyond the biochemical stage and made available for the generation or origin of hydrocarbons in a later period under geophysical influences.

There is great need of microscopical and microchemical as well as further optical examination of oil and other bituminous shales in order definitely to ascertain whether any of the waxy or fatty particles or flocculent aggregates are of animal derivation. The samples examined by Gümbel should be re-studied and subjected to conclusive tests.

THE TYPES OF SAPROPELIC DEPOSITS

As will have been inferred, the type of sapropelic deposits in the peat stage depends on the kinds of ingredient raw material, the rate of its contribution, the water conditions of stagnation, temperature and salinity or alkalinity, and the rate of collateral inorganic mineral deposition. Variation in the kinds of raw material is apparently even more important in the sapropelic deposits than in the humic.

The typical sapropelic ensemble laid down under moderately favorable circumstances consists of a slimy organic ooze derived from varying pro-

portions of plant and animal matter, mostly minute or microscopical, mingled with the remains of larger organisms and perhaps with some wind-blown debris, with more or less fine inorganic matter, all in an environment of decomposition, putrefaction, and fermentation.

Black Shales

In most bituminous shales, including those with low percentages of organic matter, the organic debris visible in microscopical sections is, in general, relatively meagre, consisting mainly of scattered vestiges of the most resistant plant matter. The black shale of the Devonian of western New York, Ohio, Illinois, Kentucky, and Tennessee, consists mostly of thinly laminated, argillaceous silts or muds, in which resinoid or waxy spore cases and spores, mostly of large size and of various types, are sparsely scattered, with some cuticular material in small bits. Conodonts are rather widespread in certain zones of the shales, in which they constitute almost the only remains of animal life, but they are always exceedingly rare in comparison with the spores. The bedding planes, seen under the binocular, show occasional trails, some of which are presumably made by worms. Various small, inorganic bodies resembling coprolites are present. Traces of algæ of delicate types also occur, but in most specimens are not structurally preserved.

Plant remains in most cases are found carbonized in much greater abundance in the blacker and more highly organic shales, but even in some of the very dark shales the preserved vegetable debris may be hardly more noticeable than in some shales less black, though the hardened colloidal decomposition matter may be more or less distinctly in evidence. The spore cases are amber colored, yellow to brown, whereas the petrified woods of the same formations, usually nearly black, in thin sections are stained more or less brown by humic matter. In richer deposits spores may be most abundant, and partially carbonized algæ may be numerous.

The divergent views as to the environmental conditions of deposition of black shales: the theory of deep, dense, semi-stagnant water such as the Black Sea, advocated by Clarke;[520] the theory of deposition in tranquil holes, not necessarily deep, as believed by Schuchert;[521] that of sedimentation in relatively shallow seas in reach of oceanic currents, as believed by Ulrich[522] to be illustrated by the Utica shales; and the theory of deposition in shallow stagnant estuaries or sounds, as described by Twenhofel,[523] are

[520] Mem. 6, New York State Mus., pt. ii, 1903, p. 199.
[521] Pop. Sci. Monthly, 1910, p. 598.
[522] Bull. Geol. Soc. Am., vol. 22, 1911, p. 358.
[523] Am. Jour. Sci., vol. 40, 1915, p. 272. See topic Black Shales.

briefly reviewed by the last named geologist. From the foregoing pages it is clear that a degree of tranquillity of water is essential even where the rate of contribution of raw material is high in order to permit conservation of the decomposition products. Spores, which have maximum resistance, may be laid down where stagnation or humic conservation is at the minimum requisite. They are present even in gray and white sandy sediments, by no means of a deep sea type, whereas the widespread extent of the beds in the epi-continental seas seems to predicate but moderate tranquillity. Some degree of acidity is, however, indicated by the general restriction of molluscan faunas.

As is suggested by Twenhofel, the ordinary black clay shales found here and there in the coal measures differ somewhat in composition as well as in conditions of deposition from the Devonian black shales. The sections generally reveal large proportions of minute carbohydrate debris and carry humic colloidal products largely derived from land flora or carbohydrate matter.

That the "humic" matter in the black shales consists of humic derivatives and carbonized (or "bituminized") vestiges, and not of petrolic hydrocarbons, is proved by the practically negligible action of petroleum solvents.

In certain zones, scattered Lingulas or Discinas are found, whereas other zones contain multitudes of young shells or small planktonic forms. Vertically the shells are far from widespread, for much of the shale records their total absence. This permits the inference that the water bodies were inhospitable or even poisonous to all molluscan life, except the relatively few forms like Lingulas which were able to persist under such unfavorable conditions. Carbonized stems, leaves, or roots of considerable diameter found at different levels; and, more rarely, logs, silicified with little or no compression, though always after partial decay, show the presence of humic derivatives toxic to carbohydrate bacteria. More toxic waters permitted the preservation of spores and carbonized spore cases, leaves, fruits, and even the thalli of Fucus-like seaweeds. Even immature oospores with their waxy-resinous envelopes have been found preserved in the interior of the carbonized thalli.[524] At Rhynie, in Aberdeenshire, Scotland, a silicified peat of Lower Devonian age preserves plant structure in marvelous detail.

In some horizons and through considerable thicknesses the bedding planes of the Devonian shales are almost or quite completely covered with resistant golden yellow or amber colored spore cases (Sporangites). However, though many plant parts have been found preserved in great detail, no deposit yet examined seems to have been marked by such concentration

[524] White, David, and Stadnichenko, T., Some mother plants of petroleum in the Devonian black shales, Econ. Geol., vol. 18, no. 3. 1923, pp. 238–252.

of toxins at the surface as to preserve absolutely the most delicate plant structures that must have been present.

The few sections of the Pierre and Niobrara of the Northern Rocky Mountain region which have been studied microscopically show little other than the resistant types of vestiges, whereas almost no vestigial matter is seen in the thin sections cut from the gray Edwards shale near Austin, Texas. The fact that appreciable amounts of hydrocarbons may be obtained from the latter by distillation, though solution tests are negative, seems to indicate that the distillate is derived from the humic derivative substances, which include complex and variable organic acid aggregates in which the higher and lower fatty acids are probably most important.

Bituminous Limestones

In bituminous limestones, spore exines, algæ, and other carbonized plant debris are often seen together with binding humic matter. The limy shale of the Platteville in southwestern Wisconsin locally contains great numbers of light yellow, refractive, lenticular bodies, probably algæ, or algal colonies, mingled with calcite crystals, grains of sand, and some albuminous matter. By distillation some of the richest of this shale yields about 30 gallons of distillate to the ton, though solvents are ineffective.

Oil Shales[525]

An oil shale is but a sapropelic shale rich in organic matter that yields considerable artificial petroleum by distillation. The average rather richly

[525] Renault, B., Les micro-organismes des lignites, Compt. Rend., Acad. Sci., Paris, vol. 126, 1898, pp. 1828–1931; Sur quelques micro-organismes des combustibles fossiles, 1893; Renault, B., and Bertrand, C. E., Note sur la formation schisteuse et le boghead d'Autun, Bull. Soc. Ind. Minér., vol. 7, 1893, pp. 449–450; Bertrand, C. E., Conclusions générales sur les charbons humiques et les charbons de Purins, Compt. Rend., Acad. Sci., Paris, vol. 127, 1898, pp. 822–825; Les charbons humiques et les charbons de Purins, Travaux et Mémoires de l'Université de Lille, vol. 6, mém. 21, 1898; Nouvelles remarques sur le kerosene shale de la Nouvelle-Galles du Sud, Bull. 9, Soc. d'Hist. Nat. d'Autun, 1896, pp. 192–202; Bertrand, C. E., and Renault, B., Pila bibractensis et le boghead d'Autun, Ibid., Bull. 6, 1892, pp. 159–253; Reinschia Australis et premières remarques sur le kerosene shale de la Nouvelle-Galles du Sud, Ibid., Bull. 6, 1893, pp. 321–425; Bertrand, C. E., Un échantillon de schiste bitumineux trouvé aux Thelots, Ibid., Bull. 24, 1912, pp. 143–148; Potonié, H., Die Entstehung der Steinkohle, 6th. ed., 1920; Zalessky, M. D., Sur quelques sapropélites fossiles, Bull. Soc. Géol. France, 1917, pp. 373–379; On the nature of Pila of the yellow bodies of boghead, Lettre scientifique, No. 4, St. Pétersbourg, Feb. 1914; Takahashi, J., The marine kerogen shales from the oil fields of Japan, a contribution to the origin of petroleum, reprinted from the Science Reports of the Tohoku Imperial University, ser. iii, vol. 1, no. 2, Aug. 1922; White, D., and Thiessen, R., The origin of coal, Bull. 38, U. S. Bureau Mines, 1913; Jeffrey, E. C., The nature of some supposed algal coals, Proc. Am. Acad. Arts and Sci., vol. 46, 1910, pp. 273–290; White, D., and Stadnichenko, T., Some mother plants of petroleum in the Devonian black shales, Econ. Geol., vol. 18, 1923, pp. 238–252.

FIG. 46. VERTICAL SECTION OF OIL SHALE OF GREEN RIVER (TERTIARY) AGE, FROM SOLDIER'S SUMMIT, UTAH, 200 TIMES NATURAL SIZE

This photograph, by Doctor R. Thiessen, shows the aspect characteristic of much of the Green River oil shale, while closely resembling also many of the Paleozoic shales. The large white transverse object in the upper part represents crustacean material in cross section. Cuticular spore material and resins are present. The matrix includes much fine-grained inorganic matter.

FIG. 47. THIN SECTION CUT VERTICAL TO THE BEDDING PLANES OF OIL SHALE OF DEVONIAN AGE IN TAYLOR COUNTY, KENTUCKY, 200 TIMES NATURAL SIZE

This section, of which the photograph is contributed by Doctor R. Thiessen, shows some of the very large megaspores, such as are common in the Middle Devonian, collapsed at different levels. Associated with the megaspores in the colloidal groundmass, are fragments of cuticle, appearing shred-like in cross section, and other very resistant débris, together with grains of mineral matter. The section shows the lamination of the shales.

bituminous shale (fig. 46), such as some of the material studied by Bertrand, reveals fine-grained silts and aluminous matter with crystals of calcite, sand, mica flakes, and spherules of pyrite, in more or less distinctly laminated bedding. Mingled with this inorganic matter, which, naturally, is less prominent in the richer deposits, are spore and pollen exines and other resistant plant matter and tests and resistant parts of animals. The debris is dominantly, at least, of aquatic origin, and contains the products of animal and plant biochemical decomposition and, usually, preserved waxy or fatty plant tissues.

In the richer material, verging into boghead purity, plant parts of greater delicacy may be found, such as algal filaments or fronds, fragments of fungi (fig. 47) whose more or less decomposed or disintegrated character shows that biochemical decomposition had progressed far toward completion.

New and somewhat remarkable views as to the origin and rôle of the bodies described as fossil algæ and spores are given in a rather elaborate discussion of oil shales by Potonié.[526] In general, however, the differentiation and terms presented are unsupported either by chemical characterization or detailed microscopical demonstration.

"Protobitumens," according to Potonié, embrace the original organic substances from which bitumens are formed. They are divided into (1) stable, which include cutins, suberins, and resins, and (2) labile, which comprise a wide range of fatty substances, oils, and albumens. Waxes and coutchoucs are intermediary between these two classes. Fatty substances of plant and animal origin are the most important contributors to the bitumens. Proteins, terpenes, and balsams are less important. Carbohydrates, including cellulose and lignin, are not "protobitumens."

"Metabitumens" are insoluble in ordinary solvents, but the bitumen in them becomes soluble when heated. Bogheads are classed as stable "metabitumens." According to Potonié's views, the mother substance of oil in the shales embraces the stable "protobitumens" and the stable "metabitumens," which are formed from labile "protobitumens." With increasing depth of the deposit, the stable metabitumens produce petroleum through a series of transformations, with resulting intermediate products called "katabitumens." These substances are not regarded, however, as the principal source of oil. He holds that the labile "protobitumens" are not transformed directly into petroleums, but are first transformed to stable "metabitumens" by processes at present little understood but in which the colloidal properties of clay appear to play an important rôle.

Potonié opposes the view that oil shales and other bituminous shales

[526] Allgemeine Petrographie der 'Oelschiefer' und ihre Verwandten mit Ausblicken auf die Erdölentstehung, Berlin, 1928.

are the sources of petroleum. He concludes that black shales are formed through the liberation of gases, no liquid petroleum being produced in the course of the process. The non-argillaceous porous and cavernous rocks, because they contain liquid bitumen, even when they have been subjected to only moderate temperatures and pressures, are regarded by Potonié not only as reservoir rocks, but as the source rocks of petroleum. The conditions of deposition of calcareous sediments are believed by him to be more

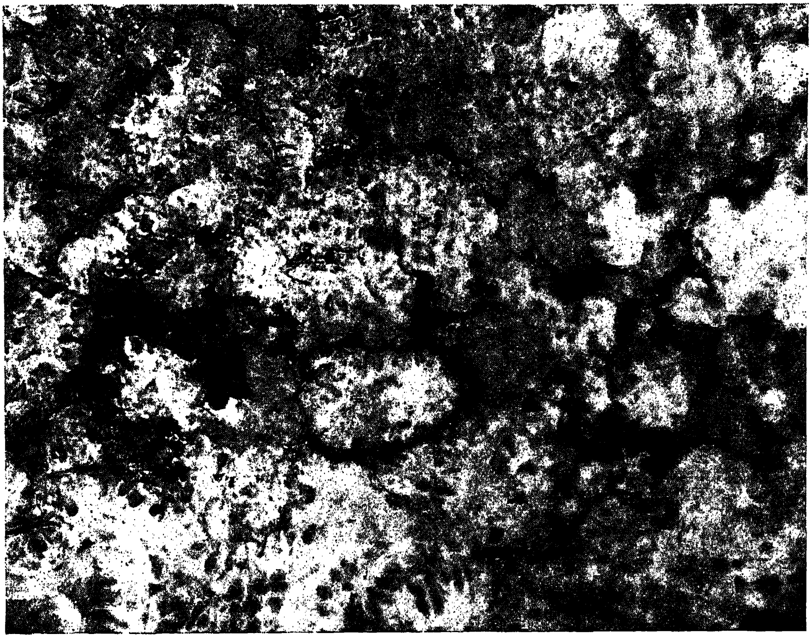

FIG. 48. THIN SECTION CUT PARALLEL TO BEDDING PLANE OF KEROSENE SHALE OF PERMO-CARBONIFEROUS AGE FROM NEW SOUTH WALES, 350 TIMES NATURAL SIZE

In this boghead the compound colonies of the alga *Reinschia australis* are in some cases clearly defined, the individual cells being readily distinguished by the oval or pyriform dark cell cavity. In some cases the primitive laminæ may be distinguished from the internal thickening on the one hand, and from the cementing tissue of the colony, on the other. The section represents a very pure deposit, in which the algæ, in general, are well preserved, although the preservation is not the most perfect. Material such as this, when not too far devolatilized, may yield 125 gallons of distillate to the ton of rock.

favorable for the preservation of the labile protobitumens, and lime is regarded as accelerating their conversion to petroleum. Porous sandy rocks are also regarded as primary sources of petroleums, labile "protobitumens" being produced in sapropelite sands under the conserving influence of salt. According to his view, a deposit containing mainly stable "proto-

bitumens" or even less mobile forms of labile "protobitumens" results in a coaly oil shale or sapropelitic coal.

The rich deposits of oil shale may be black like the kerosene shale of New South Wales (fig. 48); blackish or brownish black with satiny luster, like some of the Scotch deposits; brown like the Tertiary oil shale of eastern Brazil; buff or reddish like the Platteville oil shale; or verging into dark red like some of the Esthonian deposits. Oil shales may be canneloid, with apparent massiveness and conchoidal fracture, banded or variously streaked in the most refined lamination, or earthy. Most of them weather in laminæ, some of which are flexible and paper-thin. Nearly all are tough, and somewhat elastic or even leathery.

"Closterite"[527] is a dense, laminated, brownish-red, canneloid material from the basin of the Olkha, a tributary of the Irkoutsk River in Siberia, which consists of an accumulation of spheroid algal colonies of different sizes, similar in some respects to those of *Protococcus botryoides*, among which there are disseminated great numbers of a desmid alga, belonging to the living genus, *Closterium*. This alga favors swampy waters and is adverse to waters rich in lime, on which account its presence in a deposit acid with humic matter is readily understood, as also is the excellent preservation which still discloses the remains of chromatophores and even of pyrenoids.

"Tcheremkhite"[527] is an alga sapropel found in the vicinity of Tcheremkhova, Russia, which consists of a yellowish or brownish-red humic mass, in which are found abundant small, reddish-brown pellets of various form, with here and there clear, yellow, cellular structure so closely resembling the Scotch boghead alga, *Pila*, as to be included in the latter genus. The deposit is interpreted by Zalessky[527] as a fluvial lagoon sapropel in which are buried pellets of peaty matter washed out from other deposits and re-embedded.

An interesting feature of certain oil shales that deserves investigation is the occurrence of crystals in the organic matter. In certain thin sections Dr. E. S. Larsen noted one or more types of minute birefringent crystals not yet identified and possibly not yet described. W. H. Bradley reports two or three types of crystals of varying characters in the organic substance of the oil shales of the Green River group.[528]

[527] Zalessky, M.D., Sur quelques sapropélites fossiles, Bull. Soc. Géol., France, 1917, p. 373. The wisdom of attempting to differentiate these as mineral types may well be questioned.

[528] Bradley, W. H., Origin and microfossils of the oil shale of the Green River formation of Colorado, Prof. Paper 168, U. S. Geol. Surv.

The Alga Sapropels

The richest bituminous sediments, the bogheads, are usually made up very largely of a single kind of plant, generally an alga, in remarkable preservation. This is due in part probably to the great abundance of this

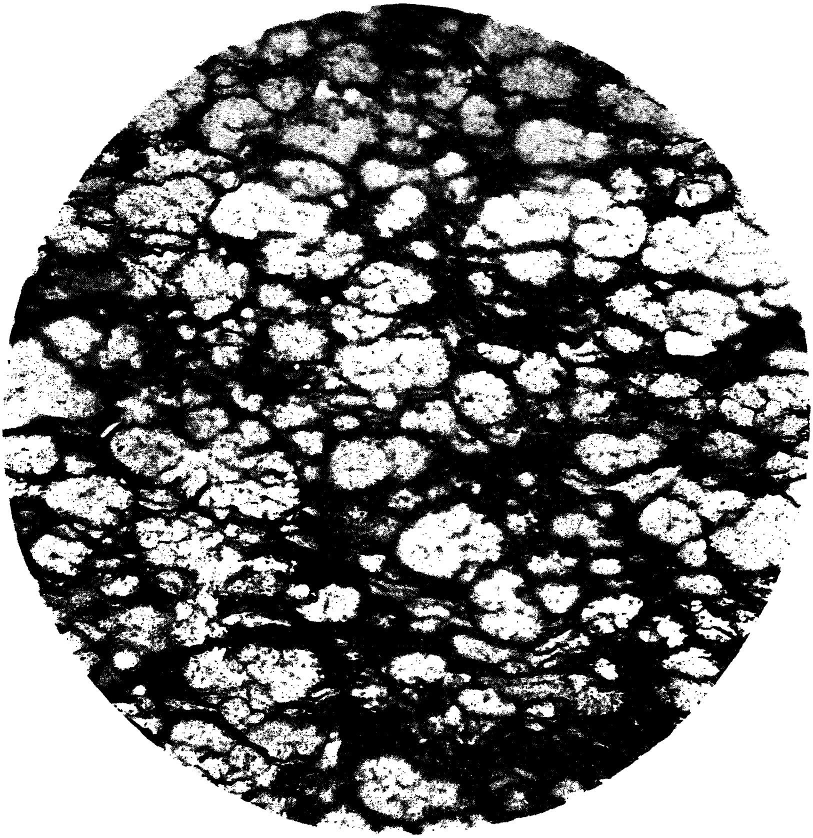

FIG. 49. SECTION, PARALLEL TO BEDDING, OF ALGAL BOGHEAD (TORBANITE) FROM LINLITHGOSHIRE, SCOTLAND, 200 TIMES NATURAL SIZE

In this section, photographed by Doctor R. Thiessen, the gray masses of sponge-like aspect are the compound colonies of *Pila scotica*, preserved as golden yellow or amber wax-like matter in the dark brown decompositional groundmass.

plant in the raw material supply and probably in part to its relative resistance, which may be due to absence of the microbes adapted to the particular types of algæ, to the development of products toxic to bacteria, or to the resistance of the chemical compounds entering into the composition of these algæ.

Among the best known of these bogheads is the Australian kerosene shale,[529] which consists almost exclusively of the compound colonies of a single alga, *Reinschia australis*,[530] the cell walls of which are lined by a wax-

FIG. 50. THIN SECTION OF TORBANITE, 1000 TIMES NATURAL SIZE

This photograph, made by Doctor R. Thiessen, shows the structure of the individual one-celled algæ as they are cemented in colonies and they later joined in compound colonies, one of which is almost wholly shown in the photograph. The colony appears to have been suspended in the gelatinous decompositional concentrate, which as the medium or groundmass appears dark in the photograph.

like or fatty deposit. The roundish or irregular cushion-shaped compound colonies, almost reaching megascopic visibility, appear as lemon yellow

[529] For analysis, see p. 428.

[530] White, D., and Thiessen, R., Origin of coal, Bull. 38, U. S. Bureau Mines, 1913, pp. 283, 297; Jeffrey, E. C., Econ. Geol. vol. 11, 1914, p. 730.

to golden yellow somewhat sponge-like masses, sometimes nearly suspended and almost uncompressed in the hardened, tough, and homogeneous, dark brown or black humic medium. The Permian bogheads near Autun in

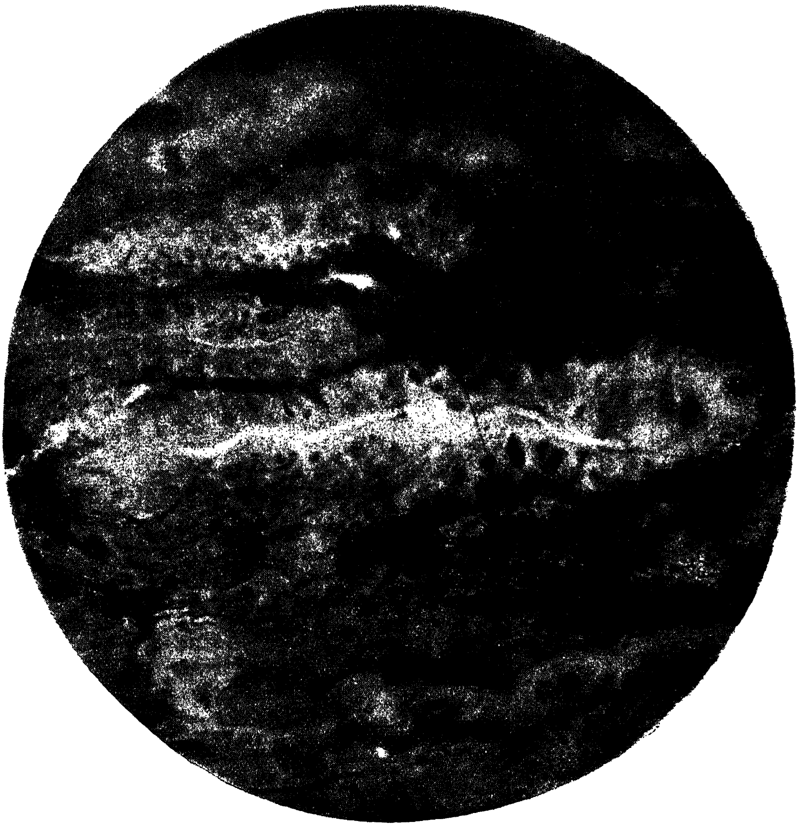

FIG. 51. VERTICAL SECTION OF BOGHEAD FROM BATHGATE, SCOTLAND, 1000 TIMES NATURAL SIZE

The photograph, made by Doctor R. Thiessen, shows the flattened compound colonies of the alga, *Pila*, in cross section. The individual one-celled algæ can be recognized by each oval cell cavity, though the walls of the individual plants forming the colony are not clearly distinguished. The white central streaks represent the now flattened internal cavity of the compound colony. In the upper middle portion of the photograph are seen parts of colonies in which biochemical decomposition has made great progress. The best preserved colonies in the section have suffered somewhat by decay; nevertheless, this boghead is comparatively pure and moderately rich. It should yield somewhere about 100 gallons of distillate to the ton.

France are formed largely from a related and similar colonial alga, *Pila bibractensis*, whereas the best Scotch oil shale, which is known as "torbanite,"

is mostly made up of another species, *Pila scotica*[530] (figs. 49–51), together with several types of supposed fungi.

Kuckersite is the Esthonian boghead[531] which, where purest, consists

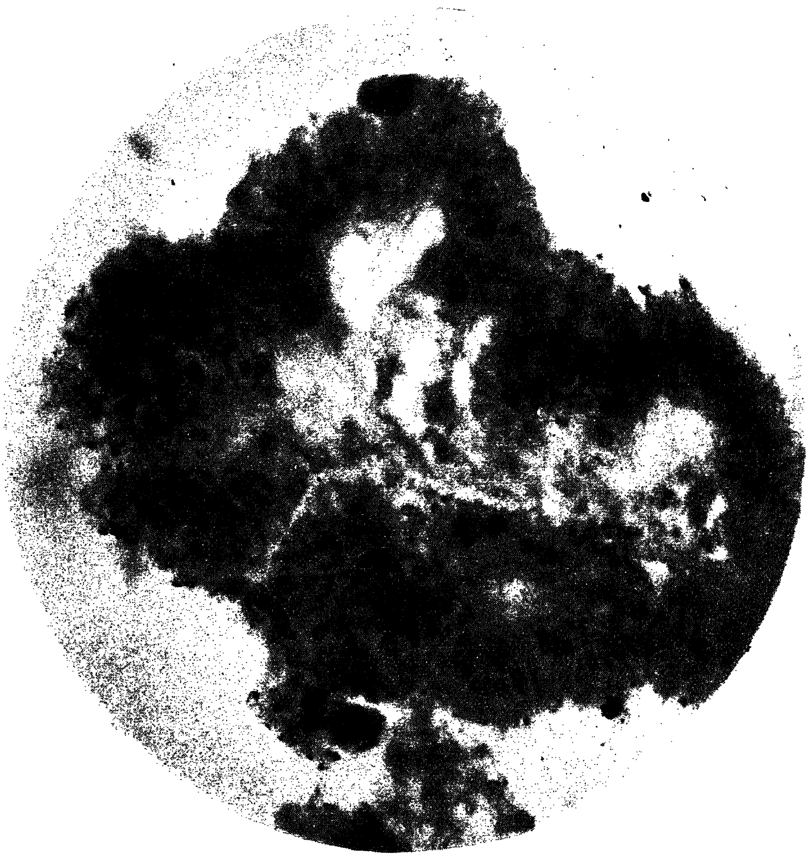

FIG. 52. COMPOUND COLONY OF ELÆOPHYTON, 1000 TIMES NATURAL SIZE

This photograph, made by Doctor R. Thiessen, is of fresh material living in the saline lake in the Coorong district of Australia. In this view the ovate or pyriform cells of the individual algæ are easily distinguished, the cell cavities appearing dark. The large solid black cells of varying size and shape filling the internal cavity of the compound colony appear white in the photograph.

almost exclusively of a colonial unicellular alga very closely resembling the living genus, *Glœocapsa.*

It is significant that, in general, where the evidence of decomposition

[531] Zalessky, M.D., Annuaire Soc. de Pal. de Russie for 1917, p. 25

is more obvious, and fewer algæ are preserved, or the preservation is less perfect, the richness falls off even beyond any relative increase in ash.

Recent Alga Sapropels

As bearing directly on the origin of bogheads and high grade oil shales and on the composition and relative resistance to decay of some of the substances produced by plant life of low orders found in them, the formation at the present day of bituminous deposits with preserved algæ under varied conditions especially deserves attention.

In the Coorong district of South Australia a greenish-gray scum or coating rises on the salty waters in winter and by evaporation and reduction of the water body is left spread on the shore and areas of exposed bottom, where it dries up and forms a thick, dark, brownish blanket that becomes elastic and is used commercially under the term "coorongite." Thiessen[532] has found this scum to consist mainly of unicellular algæ (fig. 52) with oval or ovate cell cavities and very thick walls, gelatinous or waxy in aspect, cemented by a denser substance into colonies. The individual plants and colonies are so nearly like *Reinschia* of the Permian oil shale, and *Pila* of the Mississippian boghead of Scotland, as to leave no doubt as to the very close relationship. With the algæ there are found entangled small amounts of other debris including fungi, leaf fragments, sand, etc., all matted in a heavy blanket-like crust which seems to resist further decay and is already somewhat bituminized.

Deposits closely comparable to coorongite are found in several valleys, about 50 miles south of Inhambane in Portuguese East Africa, from one of which they take their name, N'hangellite. Here the algal deposits form crusts several inches thick. They are used by the natives as fuel.[533] Similar algal accumulations are now forming in the region of Balkash Lake in Turkestan, where they are said to be as much as 12 meters thick. The algæ blow ashore and become stranded by evaporation of the water, and, as they dry, form elastic yellow mats, some of which are now found buried in sands as much as 21 kilometers from the nearest lake. Black organic crusts containing quantities of algæ, spores, etc., are also deposited in Wyoming pools following evaporation.

The ultimate analyses, given by different authors and made in different laboratories, of the above named recent sapropels, together with that of the Paleozoic Kuckersite of Esthonia, are quoted in table 57.

[532] Program and abstracts of Botanical Society of America, Boston meeting, December. 1922.

[533] Hoefer, H., op. cit., p. 269.

TABLE 57

ULTIMATE ANALYSES

	MOISTURE	C	H	O	N	S
Bernay, Coorongite	0.47	64.7	11.6	21.4		
Engler, Coorongite		77.65	11.33	11.12		
Zalessky, Turkestan		73.76	10.91	13.42	0.56	1.00
Red wood, S. E. Africa		69.63	10.35	17.52	2.50	
Zalessky, Kuckersite		64.96	8.11	(O-N 27%?)		

The examination of Coorongite in the South Australian Government Laboratory gave:

Moisture and volatile substances at 120°C	0.8
Gaseous distillates, with acid reaction	14.0
Oily distillate	69.2
Tarry matter and coke	10.1
Mineral matter	5.9
Ultimate analysis:	
Moisture	0.46
Carbon	64.73
Hydrogen	11.63
Ash	1.79
Fixed carbon	1.005
Oxygen, etc.	20.375

A sample analyzed in the United States Bureau of Mines laboratory[534] showed, on proximate analysis: moisture, 1.6; volatile matter, 90.1; fixed carbon, 2.6; ash, 5.7. Hydrogen was found to be 11.3; carbon, 73.8; nitrogen, 0.7; and oxygen, 8.4.

These recent deposits are evidently congeneric with and represent the peat stage of rich bituminous deposits of the boghead or oil shale type. They are alga sapropels in which the alga substance, seemingly fatty or waxy, and readily transformed to hydrocarbons, is apparently environed in a concentrate sufficiently toxic or resistant to prevent further decay, even after exposure to the air, in which in an alkaline and more or less arid environment it forms a black elastic bituminous deposit. Whether biochemical decomposition in the deposits has actually terminated before the sapropelic material is left stranded on the shore; whether there is any renewal of decomposition after exposure in the air; and whether the high salinity of the water has played an important part in the preservation of the plant material, are questions not yet answered.

The lamination of the sapropelic deposits may be seasonal or due, in many

[534] Thiessen, MSS.

cases at least, to the generative periods of the principal organic constituent of the raw material (figs. 53–54). The peculiar structures resembling faulting, overlapping, and even shattering of layers, all in the scale of a few inches, so often seen in some of the well known rich oil shale deposits or bogheads are probably the results of temporary exposure of the surface of the sapropelic deposit to the air. Shrinkage seems in many cases to have taken place. Very shallow water is necessarily predicated, and is, in fact, distinctly indicated in many regions.

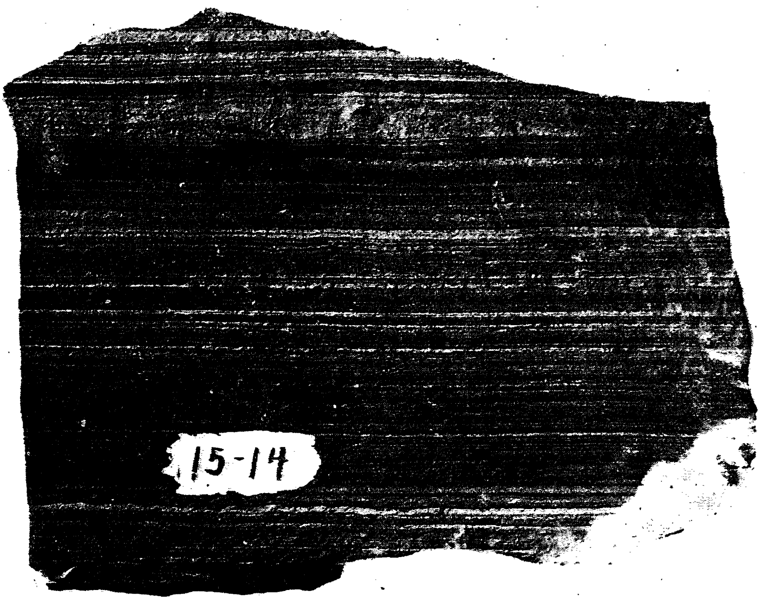

FIG. 53. FRAGMENT OF LAMINATED OIL SHALE FROM THE TERTIARY GREEN RIVER FORMATION OF NORTHWESTERN COLORADO, ABOUT $\frac{5}{6}$ NATURAL SIZE

The photograph shows the refined lamination which apparently reflects seasonal effects on the deposition of sediments. Irregularities of deposition are shown on a very small scale in the gray band in the upper part of the photograph.

Anomalous structures, which sometimes approach brecciation, are found in the richer Scotch oil shale and in some of the richest deposits of the Green River group in northwestern Colorado and northeastern Utah. In many of these deposits, as for example, in the Green River oil shales in the Uinta Basin, the organic muds were evidently subject to suncracking and scaling, and, in some cases, fragments of the scales appear to have fallen into suncracks. The concentrated humic substances, being insoluble in

water after once becoming dry, impart a degree of hardness and toughness or rigidity to the scales of suncracked organic muds, tending to preserve their integrity of form and relations when again they are submerged (fig. 55).

Records of such conditions seem to be fairly clear in the Green River shales. Here the oil shales appear to occupy nearly, or practically, filled basins which seem to have approached playa conditions. Silting up of the bottom and consequent rise of the water are shown by two or more series of low alga reefs, which are intercalated over great areas in a series

FIG. 54. FRAGMENT OF GREEN RIVER OIL SHALE, SHOWING LAMINATION, $\frac{3}{4}$ NATURAL SIZE

In the lower half is shown evidence of slight unconformities of deposition, ascribed to shallowness of water and variability in deposition. Shale from the Green River formation, Tertiary, northeastern Utah.

of low grade oil shales, scales of which, more or less rounded and mingled with sand, were washed into the hollows between the alga colonies.[535] Much calcareous oolite is interbedded with the lower part of the oil shale series.

General shallowness of the water is further seen in the air-dried slime

[535] The algal reefs together with the oolitic sands have been described by W. H. Bradley (Algæ reefs and oolites of the Green River formation, Prof. Paper 154, U. S. Geol. Surv. 1929, pp. 203–223, pls. 28–48. The reefs, the nature of which was first recognized by the writer, were originally thought by the field geologist to be nodular sandstones, which they very strongly resemble.

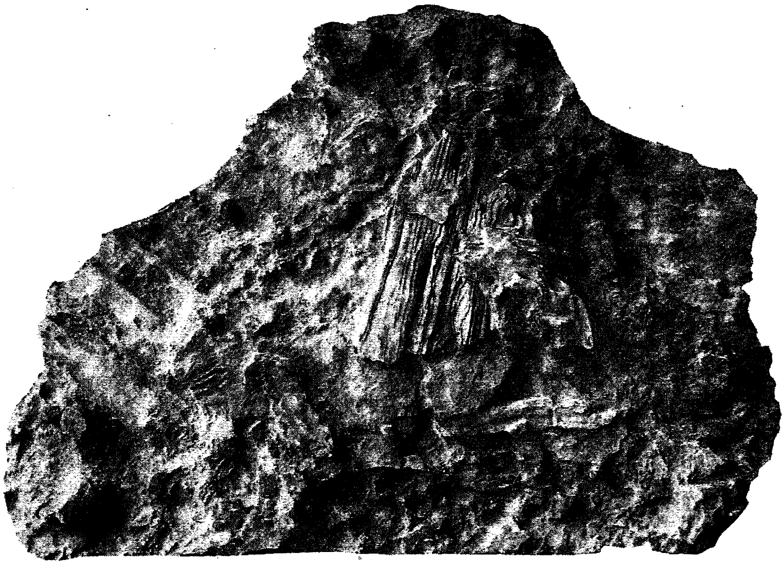

FIG. 55. SURFACE OF WEATHERED SLAB OF OIL SHALE FROM THE TERTIARY GREEN RIVER FORMATION OF NORTHEASTERN UTAH, SHOWING RESULTS OF EXPOSURE DURING DEPOSITION, ABOUT $\frac{3}{8}$ NATURAL SIZE

The organic mud, evidently slimy at times, embraces at different levels numerous irregular, once dry, fragments of similar organic mud of essentially identical composition. These were scattered in varying attitudes on the surfaces of deposition, and eventually were enveloped by sediments subsequently deposited. The differential weathering of the included scales of mud is interpreted as showing drying of the scales and probable hardening by salt precipitation, but with the readvance of the water and resumption of deposition, some scales appear to have fallen to pieces.

FIG. 56. FRAGMENT OF OIL SHALE FROM THE TERTIARY GREEN RIVER FORMATION OF NORTHEASTERN UTAH SHOWING BEDDING PLANES STREWN WITH THE SKINS OF SMALL LARVÆ, ABOUT $\frac{1}{2}$ NATURAL SIZE

These skins, found on every lamination plane through considerable thicknesses, are so numerous in places as to nearly completely cover the bedding planes. Several different species of larvæ are found at different levels.

FIG. 57. VIEW OF THIN SECTION OF TERTIARY GREEN RIVER OIL SHALE, CUT PARALLEL TO BEDDING PLANES, ABOUT 350 TIMES NATURAL SIZE

This section, photographed by C. A. Davis, shows fragments of algæ in remarkable preservation, associated with spore exines of different types and miscellaneous detrital material in a matrix consisting mainly of inorganic sediments, permeated by the concentrated humic colloid.

films so frequent in the carbonaceous portion of the formation, whereas slight unevenness of the bottom is indicated by the lenticularity of the deposits, notably the richer streaks, and in their variable thickness. Cross-bedding or current or wave action does not occur except in very small scale. Instability of the water cover, over large areas of the oil shale region[536] is indicated by the rarity of molluscan life as well as of fish and crustacea throughout most of the deposit, although the skins of larvæ of different types are, on the other hand, widespread throughout the oil shale region in northwestern Colorado and northeastern Utah, where at some levels the bedding planes of the shales are locally more or less completely covered by the skins of one species or another (fig. 56 and 57). It is inferred that the waters in the areas of sapropelic deposition were at times too acid or poisonous for the existence of animal life. There can be little doubt as to the frequent fluctuation of the Green River water cover either seasonally or occasionally during the oil shale formation period, in which it is likely that the water completely vanished from large areas at times. The temporary withdrawal of the shallow water cover from extensive areas implies evaporation of the water and consequent concentration of salts and the development of salinity or some degree of alkalinity. That such occurred is strongly suggested by the bedding plane and edge-weathering of some of the shales (fig. 58), which rather strikingly resemble silt or sandy mud that has been the seat of evaporative saline efflorescence. The relative scarcity of land plants in good preservation throughout by far the greater part of the oil shale measures may be due to a very broad fluctuating zone of mud flats between the areas clothed by vegetation and the shallow areas of deposition of sapropelic muds. On the other hand, the generally small size of the leaves, which are found in great abundance and remarkable preservation with flowers, fruits, and fungi in the vicinity of Fossil, Wyoming, and, in particular, the absence of very large leaves such as are usually found in the Eocene and Cretaceous coal fields, may provisionally be construed as suggesting a climate possibly semi-arid.

Range of the Bituminous (Sapropelic) Group

From the boghead to the lean bituminous shale, the lacustrine or marine dark shale, and the bituminous calcareous deposits, there is every degree of gradation. The richly bituminous shales containing large amounts of decompositional matter without considerable quantities of more or less

[536] For maps showing the great extent and distribution of the Green River oil shales in Colorado, Utah, and Wyoming, and for descriptions of the stratigraphy, lithology, etc., as well as for analyses and the results of tests of the Green River oil shales, see Winchester, D. E., in Bull. 729, U. S. Geol. Surv. 1923.

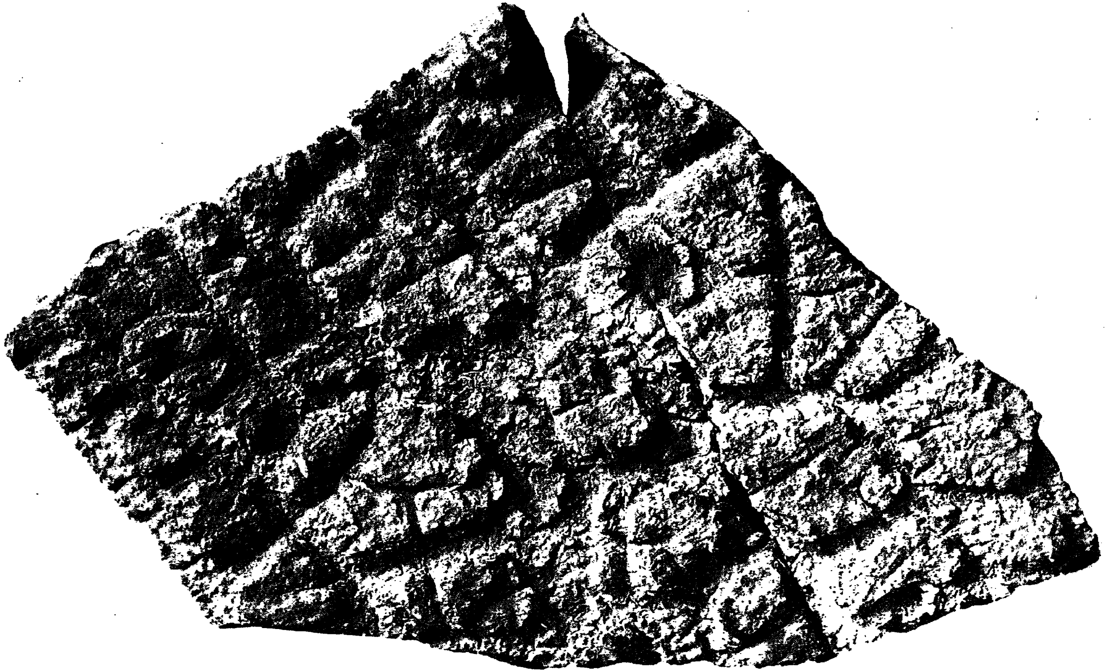

FIG. 58. WEATHERED BEDDING PLANE OF OIL SHALE OF TERTIARY GREEN RIVER AGE FROM NORTHEASTERN UTAH SHOWING EFFECTS OF MUD SCALING AND PROBABLE SALINE EFFLORESCENCE, $1\frac{1}{2}$ TIMES NATURAL SIZE

The mud after shrinkage, with some scaling, was again covered with water and the cracks filled with homogeneous sediments. The aspect of the scales *in situ* resembles scales now formed on the drying surfaces of alkaline Nevada playas, where the mud is fine grained, somewhat organic, and where evaporation permits slight efflorescence of carbonate and other salts in solution.

well preserved algæ are known as "oil shales," whereas oil shales too lean to be of importance for distillation to produce oil are classed merely as "bituminous" shales. Between the boghead and the cannel coal also, the passage is insensible.

GEOCHEMICAL CHANGES IN ORGANIC SEDIMENTS SUBSEQUENT TO DEPOSITION

Agencies of Dynamo-chemical Metamorphism

Unlike most inorganic sediments, the organic deposits, as we now find them buried in the earth's strata, have practically everywhere undergone both chemical and physical changes. Wood with perfect preservation of cell details that may have given the cellulosic or lignosic reaction in the peat stage has been more or less altered chemically, the extent of the change being dependent on the stage the deposit has reached in the course of its progressive transformation successively through lignite to anthracite, and finally graphite.

Both peat and sapropelic mud may have been loaded beneath many hundreds or thousands of feet of sediments or other rocks in subsiding basins, brought downward into zones of greater temperature, repeatedly subjected to stupendous shearing stresses for long periods of time, with further compression by expanding generated hydrocarbons and further heat of friction and chemical reaction. The causes or forces producing these changes are dynamic, and the chemical processes, in contradistinction to the preceding bio-chemical action, have been referred to as dynamo-chemical.[537] The outstanding result of the dynamo-chemical processes is the progressive elimination of the volatile matter from the organic sediments.

Results of Dynamo-chemical Influences

As results of dynamo-chemical changes both the humic and the sapropelic types will have progressively undergone physical changes, including dehydration with concurrent densification of the humic substances, reduction in volume by compression, with additional reductions by repeated losses of oxygen, carbon, hydrogen, and nitrogen, and gradual lithification, with the development of joints or cleavage in increasing refinement.

It needs to be emphasized that the complexly variant chemical components of the organic matter, whether peaty or sapropelic, at any point in this progressive dynamo-chemical alteration of the organic sediments, are even less known than in the peat stage. It has not been determined in a

[537] White, D., Some problems of the formation of coal, Econ. Geol., vol. 3, 1908, pp. 303, 311.

single natural deposit representing any stage whatever. Of deductions, calculations, and speculations as to these chemical changes there is a great mass contributed by chemists, geologists, and others, who have used ultimate analyses of the gross aggregate or of single portions in the complex mixture.[538] Just what changes the multitudes of chemical compounds entering the plant and animal tissues, secretions, and products undergo before bio-chemical action ceases is largely a matter of deduction. Still more conjectural are the chemical changes that take place in both the known and the unknown quantities as, step by step, each is chemically transformed; as, for example, the wood ceases to react for cellulose, the wax no longer reflects its original qualities and later disappears, and the many resins change their refraction and color, lose volatile matter, and finally turn to dark coaly residues.

A feature of this dynamo-chemical transformation that is both interesting and important is the survival of the plant structures, wood cells, etc., even in anthracite and graphitic coal, though emaciated by chemical reduction and deformed by compression.

It remains to the future and the labor of the zealous micro-chemist working with geophysical assistance to determine the compositions of the substances in even the most easily differentiated debris, as stage by stage, it is altered, with generation of unseen hydrocarbon products, each along its own line of evolution toward the common final residue.

It is not unlikely that close study of the coals will show the presence of crystals in the cell walls, the humic ground mass, or perhaps in other matter of organic origin. Both coals and oil shales offer interesting possibilities of discovery in the field of petrology.

ARTIFICIAL TRANSFORMATION OF ORGANIC MATTER TO COALS OF DIFFERENT RANKS

Several experimental efforts have been made to produce coal artificially from wood or peat by pressure, with or without heat. Spring[539] reported the transformation of peat at a pressure of 6000 atmospheres into a hard, black, brilliant solid, superficially indistinguishable from coal. Zeiller,[540] in the attempt to confirm Spring's results, found that peat and ulmic acid, though greatly compacted by pressures of 2000 to 6000 kilograms to the square centimeter, remained unchanged chemically, thus corroborating the tests by Gümbel[541] of lignite at 20,000 atmospheres. In 1850 Sir James

[538] See, among others, Renault, B., Sur quelques microorganismes des combustibles fossiles, 1900, p. 439.

[539] Spring, W., Bull. Acad. Roy. Belgique, vol. 49, 1880, p. 367.

[540] Zeiller, R., Bull. Soc. Géol. France, vol. 12, 1884, p. 680.

[541] Gümbel, C. W. von, Sitzungsb. Math-Phys. Classe, k. Bayer. Akad. Wiss. München, vol. 13, 1883, p. 141.

Hall made coal of a kind by heating wood in a closed cylinder, and Cagniard-Latour[542] secured similar results. Violette[543] obtained a solid residue exactly resembling a fatty coal by heating wood in a sealed tube to nearly 400 degrees. Analyses of the products are lacking in each instance. By heating non-cellulosic (a) carbohydrates and (b) ulmic acid extracted from peat in sealed glass tubes to nearly 300°, Fremy[544] secured products resembling coals both as to physical characters and chemical qualities, the carbohydrate residues being comparable to very low rank coals, whereas those from the ulmic acid matters were of higher rank. Stein[545] heated wood and water in sealed tubes to temperatures ranging from 245 to 290 degrees and obtained, according to temperature, coaly substances ranging from one corresponding roughly to peat to one nearer an average coal, though the hydrogen is generally too low.

A series of experiments on the effects of shearing pressure in the generation of hydrocarbons from various mother rocks, chiefly oil shales, conducted by J. E. Hawley and W. P. Rand, under the auspices of the Research Trustees of the American Petroleum Institute, gave results somewhat conflicting in character. It would appear that in some of the bituminous shales, such as the New Albany shale of Indiana, hydrocarbons were generated under shearing pressure at very low temperatures, especially when the experiment was continued through as long an interval as is practicable in the laboratory. In other cases the indicated results were contrariwise. It is possible that some of the apparent conflicts in results are due to losses of gases, or to oxidation of the materials in preparation.[546]

These experiments justify the inference that peat and other ingredient matters may, by means of pressure and heat at relatively low temperatures, be artificially transformed to products resembling the natural coals of different ranks. It would appear, however, that to assume a higher degree of success, material already brought to the peat stage should have been used. It is further to be remembered that the time element and the influences of the associated minerals and inorganic reactions were omitted from these experiments. The problem of laboratory alteration of peats and sapropels to coals and oil shales of successively higher ranks is a most attractive as well as important one, and it is to be hoped that experiments duplicating the natural factors, so far as practicable, will be carried out in some of our university laboratories.[547]

[542] Cagniard-Latour, C., Compt. Rend., Acad. Sci., Paris, vol 32, p. 295.

[543] Violette, Annales Chim. Phys., vol. 32, 1851, p. 304.

[544] Fremy, E., Compt. Rend., Acad. Sci., Paris. vol. 88, 1879, p. 1048.

[545] Stein, S., Chem. Centralbl., pt. ii, 1901, p. 950. For a review of the subject see Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 778.

[546] Bull. Am. Pet. Inst., Petroleum Research, Project 1, p. 3, September, 1931.

[547] It is suggested that all oxidation by contact of air with the biochemical products and other portions of the peat substance be avoided as far as possible.

SECONDARY CARBONACEOUS MATTER—BY-PRODUCTS OF ALTERATION OF ORGANIC SEDIMENTS

The conspicuous gross chemical results of the dynamo-chemical processes are progressive carbonization, with the generation and greater or less elimination of by-product gases and some liquid hydrocarbons, both consisting of carbon, hydrogen, nitrogen, oxygen, and sulphur, separately or in combination. Those in hydrocarbon combinations constitute secondary carbonaceous matter.

The humic series, embracing large proportions of oxygen, are at the lignitic[548] stage rather more than half composed of volatile matters[549] on the average. In the bituminous stage the volatile substances in the woody type range from around 46 or 47 to 25 per cent, in the semi-bituminous from 25 to 17 per cent, in the semi-anthracite from 17 to 7 per cent, and in the anthracites which verge into the graphitic, the percentage ranges from 7 per cent downward. The volatile matter resulting from the geologic distillation is believed, on the basis of laboratory experiments, to consist of gases in large amount and heavy or tarry hydrocarbons, with a variable but probably not large production of lighter liquid hydrocarbons, which may correspond in a general way to the benzol product of the retort.

In the sapropelic series and particularly in the purest alga bogheads the volatile matter may exceed 85 per cent of the combustible matter, the oxygen falling under 15 per cent in the peat stage and under 4 per cent in the bituminous rank.

The cell walls of the organic tissues remaining after biochemical decomposition are reduced in volume by loss of the volatile matter as carbonization proceeds. It would appear that the loss and corresponding shrinkage should be greater in the sapropelic group and greatest in the alga deposit, but data are wanting.

The observation of the distribution of oil pools[550] shows that commercial deposits of normal oil are not found in regions where the fixed carbon (pure coal basis) of the humic coals in oil-bearing or overlying younger formations exceeds a limit, generally 62 per cent. Beyond this point gases, asphaltic residues, and white oils in small amounts are found. In the retort most of the condensible gases are evolved at temperatures between 425° and 750°F. It is more than probable that transformations requiring 800° in the retort are accomplished at much less than 225°F. in the earth.

[548] The coals classed as lignite by the United States Geological Survey are brown. They may or may not be distinctly xyloid.

[549] All comparisons are made on the ash-, moisture-, and sulphur-free basis.

[550] White, D., Jour. Washington Acad. Sci., vol. 5, 1915, pp. 189–215; see also Min. and Met., no. 158, sec. 21, 1920, p. 7.

The Time Factor in the Geological Transformation

Reference has repeatedly been made to the importance of the geological time interval in the process of natural metamorphism of the organic sediments. It is, in fact, still the assumption of many geologists and engineers that the differences in the stages of metamorphism of coals and other carbonaceous sediments is, in general, due primarily to their difference in age, although this assumption is disproved by innumerable field observations, which may readily be confirmed. Little experimental work has, however, yet been done by way of laboratory demonstration of the importance of time. Most noteworthy of the experiments are those carried on by Maier and Zimmerley,[551] following the study of the effects of distillation of Green River shale from Soldier Summit, Utah, for varying periods. The pressures were not determined in these experiments, in which the shale was sealed in glass pyrex tubes. It was found, however, that a much lower temperature was sufficient for the transformation of the organic matter when the heat was applied for relatively long intervals. The rough formula proposed by the authors is to the effect that the time required for 1 per cent conversion at 100°C. would be 8.4×10^5 in years. This formula was later corrected by Parker D. Trask, who showed that the time required for 1 per cent conversion should be 8.4×10^4. [552]

Further attention has been given to the value of the time factor in experiments by A. J. Carlson[553] and by T. Stadnichenko,[554] the results of which have not yet been published.

In passing it may be of interest to note some of the observations recorded, with conclusions reached, by some of the experimenters. Distillation tests indicate that in most high rank bituminous coals no extensive decomposition and no yield of hydrocarbons other than occluded gases takes place below 300°C. The distillation of condensable hydrocarbons is confined in most woody bituminous coals to temperatures of 310° to 350°, but if the heating is sufficiently prolonged, the range falls between 300° and 320°.

The decomposition of the "ulmin compounds" begins above 300°, the products being gaseous paraffins, water, phenolic oils, and liquid aromatic and hydroaromatic compounds. This, the "active decomposition point," increases, however, with the rank of the ulmin compounds. It marks the

[551] Maier, C. G., and Zimmerley, S. R., The chemical dynamics of the transformation of the organic matter to bitumin in oil shale, Bull. Univ. Utah, vol. 14, no. 7, 1924, pp. 62–81.

[552] Time versus temperature in petroleum generation, Bull. Amer. Assoc. Petrol. Geol., vol. 15, no. 1, January, 1931.

[553] Carlson, A. J., Inorganic environment in kerogen transformation, U. S. Bureau Mines, Tech. Paper, in press.

[554] Stadnichenko, T., Bull. Am. Petroleum Inst., Petroleum Research, Project 3, 1931.

breakdown of their nuclear structures. Over the range of bituminous coals studied by Wheeler and his associates, with carbon content 70 to 90 per cent, the point advanced from 290° to 365°. The production of oils from the ulmin compounds is confined mainly to a temperature range of 25° to 30° above the "active decomposition point." "The simultaneous liquation and decomposition (yielding hydrocarbon oils) of resins can be detected at about 325°, continuing to about 375°. This temperature range, which is the same for all the bituminous coals examined, may be lowered slightly and narrowed if the duration of heating is prolonged."

To give a summation of some results obtained by the British investigators when heating bituminous coals of high rank:

(1) Between 225° and 300° the free hydrocarbons, soluble in the coal, are found to yield paraffins in small quantity, equal to the amount obtained by solution. Both saturated and unsaturated hydrocarbons are in nearly equal amounts.

(2) Between 325° and 375° the resins furnish paraffin and higher olefin gases. The resins and unsaturated hydrocarbons are collectively rather less than the original amount of resin in the coal.

(3) Between 300° and 320° the "structured plant entities" yield oxides of carbon and some paraffins, with liquid products consisting of unsaturated hydrocarbons, neutral oxygenated compounds, and water, the total being about 30 per cent of the original amount of plant entities in the coal.

It is to be noted that the quantity of the liquid products decreases with the rank of the ulmins, while the temperature at which they are obtained increases in coals of moderately high bituminous rank. All the oils distill below 400°.

It was found by Wheeler[554a] that, when coal from the "thick seam" was distilled, the evolution of oils was accelerated just below 300°, above which durain yielded more than vitrain by reason of an extensive production of hydrocarbon oils between 300° and 350°. Emphasis may be laid on the circumstance that the vitrain yielded more phenolic oils. Aromatic hydrocarbons predominated in the oils from vitrain, while those from durain contained a higher proportion of unsaturated hydrocarbons.

On the other hand, the Barnsley seam of the same (Birmingham) district was found to have "an active decomposition point" between 305° and 310°, which was well marked in the vitrain but less distinct in the durain. The durain produced the greater quantity of oils, particularly between 300° and 320°, the oils consisting, apart from phenolic compounds, mainly of aromatic hydrocarbons. The oils from the durains contained less phenolic compounds, while the hydrocarbons were mainly unsaturated.

[554a] Jour. Chemical Society, vol. 97, p. 1917, 1910.

The differences in character between the gases and liquid products of distillation of durain, on the one hand, and from the vitrain from the same coal, on the other, are explained as residing in the distillation products of the megaspore exines.

To an extent, at least, these experiments harmonize with the experimental results of T. Stadnichenko, showing that chemical differences distinguish many of the components of the coal or oil shale up to a relatively advanced stage of carbonization.

An interesting discussion of the temperatures necessary to have brought a series of low rank bituminous, high rank bituminous, semibituminous, and anthracites to their respective ranks of carbonization will be found in papers by Burgess and Wheeler[554b] and John Roberts.[554b] Though stimulative, it is to be borne in mind that these papers do not give necessary consideration to the importance of time, expressed in geological scale, in the metamorphic processes which have carried the sediment from rank to rank in carbonization.

The Mother Rocks of Petroleum

The carbohydrate matter of the humic or normal coal-forming deposits is generally credited with a relatively insignificant rôle in the genesis of the liquid hydrocarbons, though it takes part in the generation of methane, and possibly some other gases, with CO_2, tarry substances, and small quantities of other liquid hydrocarbons not typical of petroleums. From the waxy, fatty, and similar plant substances in the coal, petrolic oils are generated by distillation in quantities related to the ratio of such substances and doubtless have been produced underground by natural processes. It is important to note that as the fatty, waxy, or oily algæ appear in greater numbers in the deposit,—i.e., as it becomes more distinctly sapropelic—it is the more petroliferous. The richest deposits are the essentially pure alga deposits. Thus, the sapropelic or aquatic bituminous sediments must be recognized as the effective "mother rocks" or "source rocks" of natural petroleum.

The opinion has been expressed[555] that the petroleums in primitive states are formed at time of biochemical decomposition. In support of this view are the not rarely observed occurrence of oily films on swamp or richly organic terrestrial deposits, the associated gases, and the presence of natural oils in the living plants of many types. Notable among the latter are the diatoms, which contain microscopic globules of oil in the aggregate said

[554b] Proceedings 14th International Geol. Congress, p. 1855, Spain, 1926.

[555] Craig, B. C., Oil finding, 1912; see also Thompson, A. B., Petroleum mining and oil field development, 1910.

to have resemblances to petroleum. The theory of the diatom origin of petroleum has been somewhat conclusively tested in the course of researches conducted under the auspices of the American Petroleum Institute, under the immediate direction of C. F. Tolman and L. B. Becking. Neither the accumulations of diatoms which were gathered in thick beach deposits, nor the laboratory cultures, in which it was found possible to increase the oily matter to one-half the weight of the organism, were found to produce any other hydrocarbons than methane. On the other hand, the examination by Parker D. Trask of many hundreds of bottom samples of sediments from different parts of the world and from different environments failed to bring to light liquid hydrocarbons in a single instance, the conclusion being that the petroleums are generated in the course of geological processes (dynamo-chemical) acting chiefly on the organic acids either contributed directly by the organism to the sedimentary deposit or generated in the biochemical processes incident to sedimentation. The theory seems, furthermore, superfluous, in view of the observed and universally established progressive devolatilization of the sediments by incipient regional metamorphism in the course of geologic time. It is further to be borne in mind that the fossil deposits contain more free hydrocarbons or soluble bitumens than the corresponding recent sediments, a relation that has been abundantly confirmed.

Salinity and Oil Generation

So far as either commercial production or experimental tests have proceeded, they do not yet appear to have shown that the oils artificially distilled from fresh-water sapropels appreciably differ either in volume or quality from those obtained from marine deposits. The fresh-water deposits are, on the whole, purer and richer, if not more widespread. It is the belief of many that salinity is essential to oil generation. The arguments to this effect now pressed by Hoefer[556] and others are largely based on insufficient tests in the laboratory, incomplete and inadequate field observations, and lack of knowledge of the paleontological and chemical composition of the organic debris composing the richest organic deposits.

A briny medium, if sufficiently dense, would tend to conserve the animal fats, but in a brine of such strength the fish and other animals could not live, and it is certain that no such marked salinity prevailed when the fossil fish were alive. Nor can it be assumed that after the death of the fauna the salinity increased so rapidly or the entombment was so catastrophic as to preserve the animal remains before microbian action was complete. The extraordinary, or even semi-cataclysmic, conditions under which

[556] Hoefer, H., Das Erdöl, 4th ed., 1922.

animal tissues have been preserved are so restricted and rare as to be utterly inadequate as an explanation of the widespread occurrence of oil.

The examination of richly bituminous deposits, including many oil shales containing some disseminated oil, has as yet failed to reveal tissues, including fats, shown to be of animal origin.[557] Therefore, while it is possible that animal fats may have been preserved in bituminous deposits and have not been recognized under the microscope, it seems far more probable that the part played by soft animal tissues in the production of oil deposits in general can only have been through the products of the biochemical decomposition of the animal matter and the retention of these decomposition products in the humic derivative solution. These decomposition products are considered by Rae[558] as the source of petroleum; the term, "kerogen," proposed half a century ago on the supposition that it was a special chemical substance which yielded the oil on distillation, has no scientific foundation.

RELATIONS OF THE GROSS CHEMICAL COMPOSITION OF THE RAW MATERIAL AGGREGATE TO THAT OF THE ORGANIC DEPOSIT IN THE SEDIMENT AT DIFFERENT STAGES OF DYNAMO-CHEMICAL ALTERATION

The effects of the varying proportions of the carbohydrates on the one hand and the waxy-fatty-resinous components on the other in determining the chemical character of the aggregate (1) in the ingredient raw materials; (2) in the organic sediment at the end of the biochemical stage; and (3) in the subsequent dynamo-chemical stages of alteration of the humic and sapropelic types, to the lignitic, subbituminous, bituminous, and successively higher "ranks," are illustrated in table 58. The ultimate analyses, taken from various sources, are recalculated to exclude ash, moisture, sulphur, and, in some cases, nitrogen.

The contrasting initial composition both of the resinic, and fatty or oily raw materials on the one side, and of the carbohydrates on the other, and their influences on the composition of the alga boghead, the cannel, and the humic types of sediments, are, further, graphically shown in figure 59. In this illustration the carbon, hydrogen, and oxygen of the recalculated analyses are platted separately, the vertical scale in the diagram for the hydrogen being twice that shown in the curves for the carbon and oxygen. Here, as before, the analyses used in table 58 are placed in the columns of the respective ranks.

For the curves of the carbon, hydrogen, and oxygen in the humic or

[557] See reference to deep-sea dredging west of Spain, noted on p. 393.

[558] Rae, C. C., Organic material of carbonaceous shales, Bull. Am. Assoc. Pet. Geol., vol. 6, 1922, p. 333.

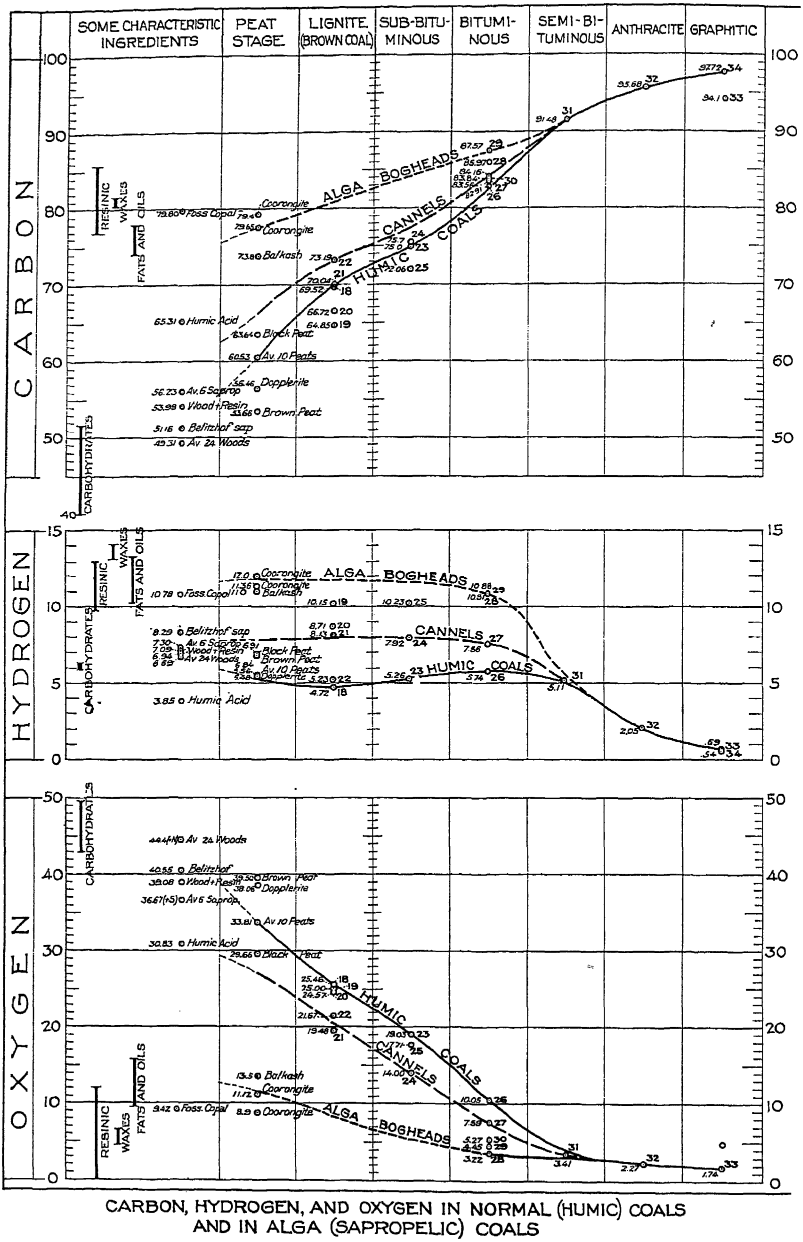

FIG. 59. CARBON, HYDROGEN, AND OXYGEN IN NORMAL (HUMIC) COALS AND IN A[LGA]
(SAPROPELIC) COALS

normal group of coals, there have been used the average of ten peats from the northern United States, most of which are more or less fibrous; the average of twenty-two lignites (brown coals) from the Tertiary of Texas; the average of two hundred and ten analyses of subbituminous coals; the average of forty bituminous coals, the average of one hundred and twenty-five analyses of semi-bituminous coal; the average of six anthracites from Pennsylvania; and the analysis of anthraxolite, a graphitized sediment from the Cambrian of Canada.

The curves for the cannel coals are based principally upon the ultimate analyses of high grade deposits from the Eocene at Lester, Arkansas,[559] the Cretaceous at Cedar City, Utah, the upper Pottsville at Lesley, Kentucky, and from a cannel lens in the Sewell coal in northern Raleigh County, West Virginia.

These curves are subject to revision when ultimate analyses of typical deposits of pure alga bogheads of lignitic and subbituminous ranks are made available, and they may be revised with great interest and profit; and in details of great importance when the analytical data are so complete that instead of showing a single composite as average for all degrees of progressive alteration within the bituminous, the subbituminous, the lignitic, or the peat ranks, it may be possible to follow the type through the successive steps of carbonization within each of these ranks. When this is done it will be possible to know at which points in the evolution of a deposit the greater eliminations of carbon, hydrogen, or oxygen occur.

The dominant effect of the carbohydrates in the raw ingredient organic materials of the humic or normal coals is clearly and conclusively shown in the high oxygen, in the low hydrogen, and in the consequent poverty of carbon in the peat as well as in the successive stages up into the semi-bituminous rank. The elimination of the oxygen is the most conspicuous and important feature of the change in the gross composition of the humic aggregate in its evolution to anthracite.[560]

While observing the origin of the humic curves near the carbon, hydrogen, and oxygen of the carbohydrates, the enriching influence of minor portions of waxy, fatty, or resinous elements in the mixture is evident. It will be noted that the humic curves, when extrapolated backward, pass in each case very close to the positions of the carbon, hydrogen, and oxygen percentages of a theoretical combination of an average wood with 10 per cent of average resin.

559 The sample analyzed also contained benches of humic lignite lying above and below the cannel lens. Here oxygen is too high and hydrogen too low.

560 Some mutual fluctuation in the carbon and hydrogen curves seen in the lignitic and subbituminous ranks, and not clearly expressed in the oxygen curve, is presumably due, in part at least, to changes in the chemical relations of the carbon and hydrogen by readjustment in the formation of new compounds.

The concentration to a degree of the resinous and resin-waxy matter of the exines, cuticles, and resins in the cannels is seen in the relatively high hydrogen curve of the typical cannel coals of different ranks, though the effect of the carbohydrate source of the humic derivative binder is evident, especially in the moderate oxygen. This is noticeable in all the cannels, including tasmanite, shown in table 58, and it is probable that the humic decomposition matter is likewise responsible for the comparatively high oxygen in the recent and Miocene sapropels of the ordinary types.

On the other hand, the curves for the rich alga sapropels are not less remarkable for their wide divergence in the bituminous and lower ranks from the curves of the humic coals than for the directness with which they seem to spring from the hydrogen, carbon, and oxygen of the waxy-fatty-resinous elements which form the raw materials. There is no room for doubt as to the influence of these elements in the deposits, and there appears to be no alternative to the conclusion that the actual composition of the algæ in the boghead at the coorongite sapropel stage, as well as at the bituminous rank, is, in its gross proportions of carbon, hydrogen, and oxygen, closely comparable to the waxes, fats, and resins. The gross composition of coorongite suggests a waxy or fatty alga substance in a "humic" solution medium derived in part from carbohydrate or other humic matters.

The general convergence, subject to fluctuation probably somewhat greater than here shown, between the carbon and oxygen curves of the alga and humic types, as they are followed from the low to the higher ranks, should be noted, though the gap between them is wide, even in the bituminous rank. The most striking of the changes is the relative loss of oxygen, with corresponding dominance of carbon. On the other hand, it is evident that hydrogen is conserved in the alga boghead. The relative conservation of hydrogen while oxygen wanes harmonizes with the increasing saturation of the volatile hydrocarbons and the lighter gravity in general of the oils as carbonization of the residues advances from rank to rank[561] in the metamorphism of the deposits.

An important fact clearly shown in the diagram is the very rapid loss of hydrogen by alga bogheads in passing from the average bituminous into the semi-bituminous ranks. This fact, which has been confirmatively observed in the analysis of many oil shales, and which is to be seen in the cannels as well, is coordinate with the failure of important oil generation and the general absence of commercial oil deposits in regions in which the carbonization of the humic organic debris, as represented by the coals, has passed into the later phases (beyond 62 to 65 per cent fixed carbon in

[561] White, D., Some relations in origin between coal and petroleum, Jour. Wash. Acad. Sci., vol. 5, 1915, pp. 189–212.

pure coal) of the bituminous rank. Even at the lowest stage of the semibituminous rank (conventionally placed in the United States at 75 per cent

TABLE 58

ANALYSIS OF HUMIC COALS AND SAPROPELIC DEPOSITS

	SPECIMEN	C	H	O	N
Humic series					
Raw materials	Carbohydrate[1]	40.0–51.7	5.8–6.3	42.9–49.68	
	Average 24 woods[2]	49.31	6.69	44.4(+N)	
	Straw[3]	48.27	6.36	44.75	
	Starch[4]	44.44	5.88	49.68	
	Wood + 10 per cent average resins[5]	53.98	6.94	39.08	
	Humic acid[6]	65.31	3.85	30.83	
Peat stage	Average 10 peats[7]	60.53	5.56	33.81	
	Briesen brown peat[8]	51.34	6.54	37.79(+S)	4.33
	Dopplerite[9]	56.46	5.48	38.06	
Lignite	Average 22 Texas lignites[10]	69.82	4.72	25.46	
Sub-bituminous	Average 210 Mont., Wyo., Colo. and N. Mex.[11]	73.31	5.09	18.43	1.41
Bituminous	Average 40 Ohio, Ind., Ill., Ia. and Mo.[12]	82.91	5.70	9.90	
Semibituminous	Average 125 Raleigh and Fayette cos., W. Va.[13]	89.08	4.98	3.32	1.57
Anthracite	Average 6 Penn. anthracites[14]	93.73	2.01	2.22	0.84
Graphite	Graphitic coal, R. I.[15]	94.10	0.69	4.81	0.25
	Anthraxolite[16]	97.72	0.54	1.74	
Sapropelic series					
Raw materials	Resinic matters[17]	76.8–85.7	9.7–12.9	0–12.12	
	Waxes[17]	80.3–81.6	13.1–14.1	4.5–6.6	
	Fats and oils[17]	74–78	10.2–13.4	9.4–15.7	
	Copal, Madagascar[18]	79.80	10.78	9.42	
	Sapropel, calcareous[19]	48.61	7.88	38.53(+S)	
	Average of 6 sapropels[20]	53.07	6.69	34.61(+S)	
Peat stage	"Mature" peat[21]	63.64	6.91	29.66	
	Coorongite[22]	79.40	12.00	8.90	0.7
	Coorongite[23]	77.65	11.33	11.12	
	Balkash Lake[24]	73.80	11.0	13.50	0.6

TABLE 58—*Concluded*

	SPECIMEN	C	H	O	N
	Sapropelic series—*Concluded*				
Lignite	Miocene, Randecker Maar[25]	64.06	10.03	24.70(+S)	1.21
	Miocene, Darmstadt[26]	65.16	8.51	23.99(+S)	2.34
	Debeque, Colo.[27]	70.04	8.13	19.43	
	Lester, Ark.[28]	71.43	5.11	21.17	
Sub-bituminous	Cedar City, cannel[29]	75.01	7.92	14.00	
	Oberkirchen[30]	71.28	10.12	17.51(+S)	1.08
Bituminous	Leslie, Ky., cannel[31]	83.56	7.56	7.59	
	Australian boghead[32]	85.97	10.81	3.22	
	Scotch boghead[33]	87.57	10.88	4.45	
	Tasmanite[34]	83.84	10.89	5.27	

[1] Thiessen, R., Bull. 38, U. S. Bureau Mines, 1913, p. 291.

[2] Clarke, F. W., Bull. 770, U. S. Geol. Surv., 1924, p. 757.

[3] Thiessen, R., op. cit.

[4] Thiessen, R., op. cit.

[5] Theoretical composition of average wood plus 10 per cent of resinous material, Thiessen, R., op. cit., p. 293.

[6] White, D., Econ. Geol., vol. 3, 1908, p. 310.

[7] Average of 10 peats from northern United States, Bull. 38, U. S. Bureau Mines, 1913, p. 292.

[8] Brown peat (Saprocoll) near Briesen, West Prussia, Späte, F., op. cit., p. 66.

[9] Composite by Muhlberg of dopplerite, Kaufmann, F. G., Jahrb. K.-k. Geol. Reichsanst., vol. 15, 1865, p. 283; Clarke, F. W., Bull. 770, U. S. Geol. Surv., 1924, 763.

[10] Average of analyses of 22 lignites, Clarke, F. W., op. cit. p. 766.

[11] Composite of analyses made in the United States Geological Survey and United States Bureau of Mines of 210 bituminous coals of Montana, Wyoming, Colorado, and New Mexico. See Bulls. 22 and 85, U. S. Bureau Mines, 1913, and 1914.

[12] Composite of analyses of 40 bituminous coals from Ohio, Indiana, Illinois, Iowa, and Missouri, Clarke, F. W., op. cit. p. 770.

[13] Composite of 125 analyses made in United States Geological Survey and United States Bureau of Mines of semi-bituminous coals of Raleigh and Fayette counties in the New River field, West Virginia. These coals range from 75 to 83 per cent fixed carbon in pure coal (ash-, moisture-, and sulphur-free), see Bulls. 22 and 85, U. S. Bureau Mines, 1913 and 1914.

[14] Average of analyses of 6 anthracite coals from Pennsylvania, Bulls. 22 and 85, U. S. Bureau Mines, 1913 and 1914.

[15] Graphitic coal from Rhode Island, average of 9 samples analyzed in the laboratories of the United States Bureau of Mines and the United States Geological Survey. These analyses vary considerably in the determinations of oxygen, which contains the residual error, for reasons well understood by chemists.

[16] Anthraxolite from a coaly deposit in the Cambrian, near Sudbury, Canada, Ellis,

W. H., Chem. News, vol. 76, 1897, p. 186; Coleman A. P., 6th. Ann. Rept., Ontario Bureau Mines, 1897; Clarke, F. W., op. cit., p. 772.

[17] Average for coniferous resinoles and resinilic acids, Thiessen, R., op. cit., p. 293. For additional analyses of resins see Tschirch, A., Die Harze und die Harzbehalter, 1906, and Späte, F., Die Bituminierung, 1907, p. 68.

[18] Copal from Madagascar, Späte, F., op. cit.

[19] Calcareous sapropel from Belitzhof near Berlin, Späte, F., op. cit., p. 46.

[20] Average of 6 recent sapropels from Germany; sulphur included with oxygen, Späte, F., op. cit., 42.

[21] "Mature" peat, evidently sapropel, Clarke, F. W., op. cit., p. 760.

[22] Coorongite from South Australia, unpublished analyses by U. S. Bureau Mines; See Thiessen, R.

[23] Engler, C., in Hoefer, H., Das Erdöl, 4th. ed., 1922, p. 269.

[24] Balkhash Lake, Turkestan, Hoefer, H., op. cit., p. 263.

[25] Brown to whitish calcareous paper coal (Dysodilkalk) in the Miocene of the Randecker Maar, Germany, Späte, F., op. cit., p. 46.

[26] Sapropelic clay, from the Miocene near Darmstadt in Germany, Späte, F., op. cit., p. 46.

[27] Rich oil shale from the Green River formation near DeBeque, Colorado; contains a little over 1 per cent of nitrogen, Winchester, D. E., Bull. 729, U. S. Geol. Surv., 1923, p. 16.

[28] Brown lignite about 5 feet thick containing elongated lens of high grade cannel, $2\frac{1}{2}$ feet thick. Sample includes the xyloid or normal lignite as well as the inclosed cannel, and therefore does not represent the oxygen and hydrogen values of the cannel, Bull. 22, U. S. Bureau Mines, 1913; see White, D., Bull. 38, U. S. Bureau Mines, 1913, pp. 16–19, 48.

[29] Cannel coal from the Colorado group of the Upper Cretaceous at Cedar City, Iron County, Utah, White, D., op. cit., p. 25, and Richardson, G. B., Bull. 341, U. S. Geol. Surv., 1909, p. 393.

[30] Bituminous coaly shale from the lower Wealden at Oberkirchen in Schaumberg-Lippe, Germany (sulphur included with oxygen), Späte, F., op. cit., p. 47.

[31] Cannel coal at Leslie, Kentucky, contains a few preserved algæ, though most of the material is spore exines with some cuticles and resins, White, D., op. cit., pp. 44, 48.

[32] Alga boghead ("kerosene shale") from New South Wales; see Renault, B., Micro-organismes des combustibles fossiles, 1893; see also Späte, F, op. cit., p. 67.

[33] Rich alga boghead, Renault, B., op. cit.; Späte, F., op. cit., p. 67.

[34] Tasmanite, a deposit made up almost entirely of exines of a single megaspore, Späte, F., op. cit., p. 68; see Jeffrey, E. C., Jour. Geol., vol. 23, 1915, p. 220.

of fixed carbon in "pure coal"), the percentages of volatile matter in the cannels and boghead types are but little larger than those of the normal humic coals; and as the semi-bituminous coals approach the rank marked by 78 per cent of fixed carbon, there appears to be little or no distinction as to the percentage or qualities of the volatile matter between the humic, cannel, and sapropelic types.

The chemical distinctions between the humic, cannel, and sapropelic types in the initial and intermediate ranks are obliterated as dynamo-chemical alteration proceeds to the anthracite and higher ranks. This final step of carbonization, graphically shown in the curves, is abundantly

corroborated by analyses of semi-anthracites and anthracites as well. In other words, the ultimate phases of the organic deposits of the humic group are apparently indistinguishable chemically from the ultimate phases of the sapropelic or bituminous deposits.

"Bituminization," so-called, is a process of reduction of organic matter under water, the conspicuous feature of which is deoxidation. It continues through both the biochemical and dynamo-chemical changes of the organic substances, including both debris and derivatives. It is an essential phase of the changes resulting in the carbonization of the organic debris and the humic derivatives. It is inseparable from "coalification," which covers the progressive changes undergone by the preserved organic debris between the death of the organisms and the stage of complete carbonization.

In every study of the problems of the generation of petroleum or any hydrocarbons from the various supposed mother rocks, such as oil shales, bituminous shales, alga shales, carbonaceous shales, and so forth, it is always to be remembered that the rocks under examination are residual deposits from which varying amounts of volatile products have already been eliminated in the course of the progressive incipient metamorphism which follows the processes of sedimentation. This is true of coals as well as other carbonaceous sediments.

Sedimentary Deposits of Iron Minerals[562]

SOURCES AND TRANSPORTATION OF IRON-BEARING SEDIMENTS

Nearly all rocks contain more or less iron, which in the processes of rock destruction is released and carried to the places of deposition by wind and water. The released material is usually in the forms of oxides or hydroxides, carbonate, sulphate, and in some cases chloride. Because of the high insolubility of the oxides and hydroxides, they are apt to remain at, or near, the places of release.

Deposits made by wind contain such small quantities of iron that they may hardly be referred to as iron-bearing sediments, and hence are disregarded. Waters carry iron in solution, in the colloidal state, in suspension, and by traction. That carried in visible suspension and by traction is small in amount as a rule, and consists mainly of iron minerals mechanically released from the parent rock and the oxides and hydroxides resulting from decomposition. Suspended ferric hydroxide may be seen as flocculent particles in some waters, and it is very commonly observed floating on the

[562] In the preparation of this topic for the first edition, a manuscript contributed by Doctor E. C. Harder was of great assistance in considering some phases of the iron bearing sediments. The material of the first edition has been freely used in preparing the manuscript for the second.

surface of stagnant waters as opalescent films, frequently mistaken for oil by the uninformed.

Iron appears to be carried in solution mainly as ferrous bicarbonate, some is carried as ferrous sulphate and ferrous chloride; and some may be in the form of organic compounds. The bicarbonate remains in solution as long as there is an excess of carbon dioxide and a deficiency of oxygen, but when the former falls below the necessary quantity, the iron usually is precipitated as ferric hydroxide. The relations between the quantities of carbon dioxide and ferrous bicarbonate necessary to hold the latter in solution need to be determined. As a part of the entire matter in solution in surface waters, the ferrous bicarbonate is small.

The extents to which iron is carried in stream waters as the sulphate and chloride are not well known. Ferrous sulphate is invariably present in underground waters which pass through rocks rich in sulphide minerals, and it is probable that some is present in most surface waters. Available information seems to indicate that where both the carbonate and sulphate radicals are present in surface waters, the iron is more readily held in the bicarbonate form. The quantity that may be held in either form in relatively different concentrations is unknown.

Nothing definite is known relating to the occurrences of iron salts of organic acids in surface waters, but the literature contains many references to their presence. They have generally been designated by the rather indefinite term of ferri-humates and ferro-humates. Iron salts of some of the more common organic acids, as the acetates, malates, citrates, tartrates, lactates, or oxalates, may also be present in surface waters, but their identification is difficult.

It is known that iron oxide is relatively insoluble, but in most analyses of the solid matter in solution the iron is calculated as ferric oxide. If it is in this form in the water, it is probable that it is in the colloidal state and is not removed in filtering. It is Gruner's[563] opinion, based on experimental data, that larger amounts of iron "are carried as organic colloids or adsorbed by organic acids" than as the bicarbonate of iron, and Moore and Maynard[564] advance the suggestion that "the greater portion of the iron carried in natural waters high in organic matter is in the condition of a ferric oxide hydrosol stabilized by the organic colloids in the water, and that smaller quantities are carried in salts of organic and inorganic acids," and by experiment they show that "As much as 36 parts per million ferric

[563] Gruner, J. W., The origin of sedimentary iron formations, etc., Econ. Geol., vol. 17, 1922, p. 445.

[564] Moore, E. S., and Maynard, J. E., Solution, transportation and precipitation of iron and silica, Econ. Geol., vol. 24, 1929, pp. 299–302.

oxide, formed by the oxidation and hydrolysis of ferrous bicarbonate, can be held in colloidal solution by 16 parts per million organic matter."

The average content of iron in the rivers and lake waters of North America is less than one part per million,[565] ranging from a mere trace in many waters to 3.33 per cent of the solids in solution in the Merrimac River above Concord, New Hampshire.[566] The average iron content of the solid matter in solution in the river waters of the world is 2.75 per cent.[565] The highest figure seen for waters of any extent is that for the Waini River of British Guiana, of which 15.78 per cent of the solid matter in "solution," or nearly 7 parts per million, is ferric oxide. Moore[567] found streams and lakes in Ontario with a ferric oxide content ranging up to 61 parts per million.

Gruner's[568] experiments with silica and iron in peat solutions showed that the two substances are relatively stable in such solutions, precipitating very slowly and more or less incompletely, and that electrolytes in solution in sea water are not effective as precipitants. He found that river and swamp waters rich in organic matter may carry large quantities of iron and silica, and pointed out that the Amazon River with an average iron content of 3 parts per million could transport to sites of deposition 1,940,000 million metric tons of iron in 176,000 years. This is the quantity of iron estimated to be present in the Huronian Biwabik formation. Two to three times as much silica would be transported during the same interval; the quantity of alumina would be small. Moore and Maynard[569] found that "the proportion of iron carried in solution is dependent upon the relative quantity of organic matter in solution," and that the "proportions of lime, magnesia, and bicarbonate, do not materially affect the proportions of iron carried."

The generally slight quantities of iron carried in solution and in the colloidal state in surface waters have made it difficult to understand how these small quantities could have been responsible for the vast accumulations of iron oxide which occur in the Pre-Cambrian systems of parts of the world. The matter has been the more difficult to understand because of the assumption that the land vegetation of those early days was negligible, thus giving less opportunity for the iron to enter into solution as bicarbonate. The assumption of sparseness of land vegetation may, however, be in error, as the sediments contain much carbonaceous matter and even coal is said to

565 Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 119.

566 Clarke, F. W., op. cit., 1924, pp. 74–119. Al_2O_3 is included in some of the figures, but Gruner (op. cit., p. 454) suggests that the quantity is small.

567 Moore, E. S., Econ. Geol., vol. 5, 1910, p. 533; 18th Rept. Ontario Bureau of Mines, 1909, p. 192.

568 Gruner, J. W., op. cit., pp. 421, 454–455.

569 Moore and Maynard, op. cit., 1929, pp. 291–292.

be present.[570] Moreover, the atmosphere may have been largely composed of carbon dioxide.

As these Pre-Cambrian iron deposits are associated with much silica, a common source has been sought for both substances. Considerable clastic material is present, and evidence of shallow-water deposition is suggested by cross-lamination and ripple marks. These features have suggested rapid deposition. The introduction of clastic matter may have been an occasional incident in the depositional history, and cross-lamination and ripple marks are constantly forming in waters which are receiving no or few sediments. These ferruginous and siliceous sediments may therefore have been deposited with exceeding slowness in waters receiving little other than iron and silica, both being carried as colloids in waters rich in organic matter, thus not requiring sources other than those well known.

Some iron and silica deposits are associated with igneous rocks, and this has suggested that emanations from the original lavas may have contributed iron and silica to waters in, or adjacent to which, lavas cooled. As lavas approach the surface, it has been suggested that there may be considerable intervals during which springs of magmatic waters exist at the surface. These magmatic waters have been postulated to carry iron and silica. Appeal has been made to this hypothesis or some modification of it to explain the iron and silica deposits of the Lake Superior region,[571] and the Franciscan cherts of California.[572] In the Lake Superior region it may be that the iron and silica were derived from springs containing magmatic waters rich in these substances, and some of these waters may have been anticipatory to the later great Keweenawan lava flows. The hypothesis is further considered in connection with the origin of the Lake Superior iron formations and the origin of chert and flint.

AGENTS AND ENVIRONMENTS OF DEPOSITION OF IRON-BEARING SEDIMENTS

Iron may be precipitated from solution by chemical-organic processes which form ferric oxides and hydroxides, ferrous carbonate, hydrous ferrous and ferric silicates, iron phosphates, basic ferric sulphates, and ferric and ferrous sulphides. In the precipitation of the ferric hydroxides and the sulphides biologic agencies are thought to play a considerable rôle. The other compounds are believed to be inorganic, chemical precipitates, but

[570] Grabau, A. W., Comprehensive geology, vol. 2, 1920, p. 289.

[571] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior Region, Mon. 52, U. S. Geol. Surv., 1911, pp. 504, 518.

[572] Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. California Publ. Dept. Geol., vol. 11, no. 3, 1918, pp. 383–386.

in the case of some of the silicates, sulphates, and carbonates the presence of organic matter is again a factor in the deposition. Where iron-bearing solutions come in contact with oxidizing conditions, permitting the escape of the carbon dioxide by which the ferrous carbonate is held in solution, ferric hydroxide is precipitated. Iron is thought to be precipitated as carbonate in places of abundance of plant and other dead organic matter. If alkaline silicates are abundant in the water, silicates of iron may result. If phosphorus is present, it is apt to accompany the precipitation of any iron salt.

Iron compounds transported by traction and visible suspension come to rest at those places where the capacity and competency of the transporting agents decrease consequent to slowing up of velocity.

It seems probable that iron carried as the colloid to the ocean by streams is precipitated almost immediately by colloids of opposite sign and by the electrolytes in solution in ocean waters, the precipitating power depending on the electrolytes and their valencies. The same thing may occur where two waters meet, as where streams enter lakes or at the junction of two streams. Negative ferric oxide hydrosols containing 227 parts per million ferric oxide have been found to be precipitated by 659 parts per million potassium chloride, 886 parts per million sodium chloride, 320 parts per million potassium sulphate, or 2894 parts per million sodium hydroxide. Double and quadruple concentration of ferric oxide showed that greater concentration of electrolytes was necessary for precipitation. Positive sols of ferric oxide were found to react more or less similarly, and it may thus be stated that experiment has demonstrated that both positive and negative ferric oxide hydrosols ranging in concentration from 50 to 1000 parts per million are precipitated by electrolytes in concentrations ranging up to 13,000 parts per million. As the concentration of sea water is 34,400 parts per million, it is obvious that there is little possibility of colloidal iron escaping precipitation after the sea is reached.[573]

The environments in which iron sediments are deposited are chiefly those of quiet waters, as bogs, marshes, lakes, lagoons, and the sea. They are deposited in streams, but the deposition usually occurs in quiet water preceded up-stream by agitated water. Carbon dioxide escapes in agitated water, and the iron is precipitated in flocculent masses which settle in the quiet water. Iron is also precipitated in places where iron-bearing solutions issue from the ground.

Several iron compounds may be formed and deposited in both fresh and salt water; some, as glauconite, appear to be confined entirely to marine environments.

[573] Sen, K. C., Canguly, P. B., and Dhar, P. B., Jour. Phys. Chem., vol. 28, 1924, pp. 316–318; Moore and Maynard, op. cit., 1929, pp. 365–371.

The problems of deposition and environment are further considered in connection with the different types of iron-bearing sedimentary products.

THE IRON-BEARING SEDIMENTARY PRODUCTS

The iron-bearing minerals which occur in sediments in sufficient abundance to be worthy of consideration, arranged in the order of probable quantitative importance, are: hematite, limonite, siderite, magnetite and ilmenite, glauconite, greenalite, chamosite and other iron silicates, pyrite, marcasite, and melnikovite. All of these substances seem to be capable of original deposition, but it is sometimes difficult to state whether the present condition of an iron-bearing terrane has the iron in the form in which it was originally deposited. The iron deposits of the Lake Superior region are considered by many geologists to have attained their present condition largely through alteration subsequent to deposition, and little agreement has been reached with respect to the original form of the oolitic iron deposits of the Appalachian Clinton, as well as similar iron deposits elsewhere.

The iron-bearing sedimentary products are grouped into the four divisions of oxides and hydroxides, carbonates, silicates, and sulphides. These are considered in the order named.

Iron Oxides and Hydroxides

The oxides and common hydroxides are hematite (Fe_2O_3), magnetite (Fe_3O_4), turgite ($2Fe_2O_3 \cdot H_2O$), goethite ($Fe_2O_3 \cdot H_2O$), limonite ($2Fe_2O_3 \cdot 3H_2O$),[574] zanthosiderite ($Fe_2O_3 \cdot 2H_2O$), and limnite ($Fe_2O_3 \cdot 3H_2O$). Goethite is the only hydroxide which occurs in crystalline form. Hematite and limonite appear to be most abundant. Sedimentary deposits of ferric oxides and hydroxides are rarely pure; very commonly various impurities are associated with the iron minerals, chief among which are silica, either in the form of chert or quartz, clay or minerals derived from it by metamorphism, calcium carbonate, iron carbonate, and iron silicate. One or several of these impurities may be disseminated through the iron-bearing beds, giving them a more or less homogeneous composition throughout, or the impurities may be segregated into beds or lenses of varying thicknesses interlayered with richer hematite or limonite beds.

Hematite is the most common sedimentary iron mineral, but it should not be concluded that it was thus originally deposited. In some cases the iron oxide seems to be a replacement, as may be true of the Clinton oolitic ores, and is certainly the explanation of the Clinton fossil ores. Iron-

[574] Experimental work by Posnjak and Merwin indicates that most limonites are goethite with adsorbed and capillary water and that turgite represents solid solutions of goethite and hematite with adsorbed and included water. Posnjak, E., and Merwin, H. E., The hydrated ferric oxides, Am. Jour. Sci., vol. 47, 1919 pp. 311–348.

bearing strata which are interpreted by many as having been originally deposited as oxide or hydroxide are the Minette ores of France and Luxemburg, the Pre-Cambrian ores of Minas Geraes, Brazil, and the Wabana ores of Newfoundland.

The iron oxide and hydroxide beds range in thickness and areal distribution from small lenses less than a foot thick and extending over a few acres or less, as is the case for some of the bog ores, to units of vast thickness and areal extent, as the great deposits of Brazil, the Clinton ores of the Appalachians, and the iron formations of the Lake Superior region.

The precipitation of ferric hydroxide is accomplished both by chemical and organic agencies, the reactions being accompanied by hydrolysis in ferric compounds and by oxidation with hydrolysis in ferrous compounds, the material precipitated being in the colloidal state.

The hydroxide of iron is precipitated from ferrous carbonate solutions by simple oxidation and hydration preceded by depletion of excess carbon dioxide. The following equations may express the reactions which take place:

$$FeCO_3 + H_2O = Fe(OH)_2 + CO_2$$
$$4Fe(OH)_2 + 2O = 2Fe_2O_3 \cdot 3H_2O + H_2O$$

The hydroxide may subsequently change to the oxide.

Ferric hydroxide may be precipitated from solutions of iron sulphate by the action of alkalies, by hydrolysis, or, in the case of ferrous sulphate, by combined oxidation and hydrolysis. Varying quantities of basic ferric sulphates are generally precipitated with the ferric hydroxide, but these gradually change to ferric hydroxide.

From solutions of certain organic iron salts, basic ferric compounds that gradually change to ferric hydroxide may be precipitated by alkalies or by hydrolysis, but in others such precipitation does not occur. In the latter, iron may be retained in solution for an indefinite length of time. Among the former are the acetate, oxalate, and lactate, and among the latter are the tartrate, citrate, and humates. Iron-depositing bacteria are believed to be active in the deposition of basic ferric salts and ferric hydroxide from both of these classes of salts as well as from solutions of ferrous carbonate. According to Moore and Maynard,[575] iron as ferric hydroxide is precipitated by bacteria from solutions of ferric ammonium tartrate, ferric malate, ferric formate, and ferric tartrate, the rate of precipitation not being materially affected by light or the presence or absence of oxygen or carbon dioxide.

Modern bog and spring deposits of ferric hydroxide are the only ones in whose formation bacteria are known to have taken an important part, but

[575] Moore and Maynard, op. cit., 1929, pp. 278–279.

it is not improbable that these organisms were active in the formation of many of the ancient deposits of bedded hematites. The evidence of past action is scanty, however, and it is not to be expected that such should be largely present, as the fragile nature of the organisms leads to their easy obliteration. Even in recent bog ores it is only occasionally that remains of bacteria are found, and yet practically all ferric hydroxide scums found in boggy places or in iron springs, which by consolidation form bog iron ores, consist of masses of iron-depositing organisms with ferric hydroxide in their sheaths and cell walls.

In addition to bacteria, protozoa, algæ, and fungi also are concerned in the precipitation of ferric hydroxide. Bacteria, however, stand first, and of these the most important is the group known as the "thread bacteria."

There has been considerable discussion as to (a) whether iron-depositing organisms really require compounds for their life processes analogous to the sulphur compounds used by sulphur bacteria, or the nitrogenous compounds used by nitrogen-fixing bacteria; (b) whether the organisms use iron compounds simply for the purpose of external protection, as some organisms use silica and other organisms calcium carbonate; or (c) whether the ferric hydroxide is precipitated entirely by chemical action and only collects on the sheaths of organisms because of mucilaginous coverings that many of them possess.[576]

Harder[577] has shown that probably all of these processes apply to some extent in the formation of iron deposits by organisms. However, the results obtained from experiments with the main group of iron-depositing organisms, the thread bacteria, indicate that most of the precipitation of ferric hydroxide by biological agencies is due to the life processes of the organisms. These results may be summarized as follows: (a) Certain bacteria, such as the common *Spirophyllum ferrugineum* and perhaps also *Gallionella ferruginea*, precipitate ferric hydroxide from solutions of ferrous carbonate and use the carbon dioxide liberated and the energy produced during the oxidation for their life processes. They require ferrous carbonate and cannot exist without it. Other thread bacteria, as *Leptothrix ochracea* (*Chlamydothrix ochracea*) and *Cladothrix dichotoma* and probably various lower bacteria, do not require ferrous carbonate in solution, but cause the deposition and accumulation of ferric hydroxide when iron salts are present. They probably precipitate iron from either inorganic or organic salts in solution. The first-named bacterium is abundant in iron-bearing waters of iron springs

[576] Ellis, D.; A contribution to our knowledge of thread bacteria, Centralb. Bakteriologie, Abt. 2, Bd. 19, 1907, pp. 502–518.

[577] Harder, E. C., Iron-depositing bacteria and their geologic relations, Prof. Paper 113, U. S. Geol. Surv., 1919, pp. 78–79.

and marshes, and the second is a soil organism. (c) To a third group belong bacteria which attack organic iron salts in solution, probably using the organic acid radical as food and precipitating ferric hydroxide or basic ferric salts which are gradually changed to ferric hydroxide. This group of bacteria does not utilize inorganic iron salts. The last group is not well known, but nearly all of them belong to the lower forms.

From the geologic point of view it is important to know (a) the distribution of the iron-depositing bacteria, whether limited or widespread;[578] (b) the importance of their activity in natural waters as compared with simple chemical processes; (c) the environments which permit their maximum activity; and (d) the parts they have played in the formation of the iron deposits of the past.

So far as the present is concerned, iron-depositing bacteria are present wherever iron-bearing waters occur, and the only condition necessary for their presence appears to be iron in solution. The quantity in solution need not be large, *Crenothrix* living in the waters of the city of Madison, Wisconsin, which contain only 1.8 parts ferric oxide per million. The amount of organic matter in solution has some influence on the distribution, some forms thriving best in waters in which there is little or none, others requiring a certain quantity. The extent to which the iron-depositing bacteria inhabit salt water is not known, but some of the common forms of the iron thread bacteria have been identified in iron scums found in brackish and salt water lagoons.[579] It is therefore possible that their distribution is universal. The varieties differ with locality and environment, as is to be expected. Some varieties are more abundant in iron springs, wells, and mines in which the water is relatively pure; whereas others thrive in lagoons and marshes of which the waters contain an abundance of organic matter. The conditions which permit the greatest development of activity of iron-depositing bacteria have not been carefully studied. Temperature seems to have little effect, although most of the forms now known appear to prefer cold to warm waters. Lieske states that the optimum temperature for *Spirophyllum* is 5° to 6°C.,[580] whereas Harder found that 9° to 10° is a common temperature in iron springs containing iron-depositing bacteria.[581]

Walcott[582] has described what he considered evidence of bacteria from

[578] It is known that soil bacteria, capable of precipitating organic iron solutions, have wide distribution. Moore and Maynard, op. cit., 1929, p. 279.

[579] Mr. Irving J. Bridenstine and Mr. Lloyd North of the University of Iowa have made some interesting studies of bacteria in iron scums collected in lagoons on the Texas coast.

[580] Lieske, R., Beiträge zur Kenntniss der Physiologie von Spirophyllum ferrugineum Ellis, Jahrb. wiss. Botanik, Bd. 49, 1911, pp. 91–127.

[581] Harder, E. C., op. cit., p. 81.

[582] Walcott, C. D., Discovery of Algonkian bacteria, Proc. Nat. Acad. Sci., vol. 1, 1915, p. 256.

the Algonkian of Montana, and Gruner[583] has identified them in Pre-Cambrian cherts of the Lake Superior region. Bleicher[584] mentioned rods of silica in the Minette ores of France which are said to resemble bacteria. While these evidences of bacteria are not definitely convincing and other interpretations of the factors identified are perhaps possible, it is considered very probable that bacteria of many species were in existence in the early geologic periods; and that some of them played a part in the precipitation of iron minerals may be considered reasonably certain.

The photosynthesis of green plants precipitates ferric hydroxide, the precipitation being altogether from the bicarbonate.

Hematite and also magnetite[585] may develop through the oxidation of ferric sulphate in solution according to equations as follows:

$$6FeSO_4 + 3O = 2Fe_2(SO_4)_3 + Fe_2O_3, \text{ or}$$
$$9FeSO_4 + 4O = 3Fe_2(SO_4)_3 + Fe_3O_4$$

Magnetite may also be formed at high temperatures through the reaction of ferrous iron and water according to the equation:

$$3FeO + H_2O = Fe_3O_4 + H_2$$

Some deposits of ferric oxides and hydroxides develop through mechanical methods. Rocks rich in magnetite and ilmenite which are undergoing weathering very largely through physical agencies have the lighter and smaller substances swept away and the heavier collected in the channels of streams and on beaches. Such deposits may also contain numerous particles of other heavy minerals, as garnet, rutile, zircon, and chromite. More or less quartz is also present. In streams the magnetite and ilmenite are constantly shifted downstream and ultimately carried to the sea, where they are transported along the beach and locally form deposits of considerable purity. Deposits of black sand, as the magnetite and ilmenite particles are called, have considerable extent along the beaches of northern California, Oregon and Washington, along the Columbia River, on the beaches of the north shore of the Gulf of St. Lawrence and New Zealand, on the rivers of Brazil, and elsewhere.[586] These sands are of recent origin, but in

[583] Gruner, J. W., The origin of sedimentary iron formations, etc., Econ. Geol., vol. 17, 1922, p. 418; Algæ believed to be Archean, Jour. Geol., vol. 31, 1923, pp. 146–148; Discovery of life in the Archean, Ibid., vol. 33, 1925, pp. 151–152.

[584] Quoted by Gruner, J. W., Origin of sedimentary iron formations, Econ. Geol., vol. 17, 1922, p. 420.

[585] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior Region, Mon. 52, U. S. Geol. Surv., 1911, p. 527.

[586] Mackenzie, G. C., The magnetic iron sands of Natashkwan, County of Saguenay, Province of Quebec, Canada, Mem. 145, Dept. of Mines Branch, Canada, 1912.

the Upper Cretaceous of northwestern Montana moderately consolidated beds of titaniferous magnetite sands of similar character and origin are known,[587] and it has been suggested that certain siderite and limonite ore deposits in the Ordovician near Hudson, New York, were originally deposited as magnetite sands.[588]

In Brazil there are mechanical deposits of hematite known as *canga*, rubble ores, and sand ore. The *canga* deposits are said to be large. These have been derived from the older hematites of the region.[589]

"Low level laterites"[590] are also deposits which have been transported, in some instances at least, from laterites of a higher elevation.

Important deposits of iron oxide may arise as a consequence of rock decomposition. This is not common under the conditions giving kaolin as the important end product, but under the conditions promoting laterization large deposits of iron oxide may thus form. Such deposits usually contain more or less bauxite, the range being from nearly pure iron oxide to nearly pure bauxite. Some titanium and manganese oxides are also present.[591]

According to Lacroix,[592] a typical profile of a laterite deposit from the surface downward is:

1. Iron crust, 1–8 feet thick.
2. Concretionary zone of Al-Fe hydrates, characterized by oolitic and pisolitic textures, 3–70 feet thick.
3. Bleached zone, composed of light-colored aluminum hydrates. Retains structures and textures of original rocks, 15–80 feet thick.
4. Gradual passage into original rock.

The development of laterites seems to be confined to tropical and subtropical conditions, and for their origin various explanations have been offered. Holland suggested that their production might be related to the activities of some lowly organism which required the silica for its activities, and hence separated it from the silicates with which it was combined.[593]

[587] Stebinger, E., Titaniferous magnetite-beds on the Blackfeet Indian Reservation, Montana, Bull. 540, U. S. Geol. Surv., 1914, pp. 329–337.

[588] Ruedemann, R., Age and origin of the siderite and limonite of the Burden iron mines near Hudson, New York, Abstract, Bull. Geol. Soc. Am., vol. 41, 1930, p. 57.

[589] Leith, C. K., and Harder, E. C., The hematite ores of Brazil and a comparison with hematite ores of Lake Superior, Econ. Geol., vol. 6, 1911, pp. 670–686.

[590] Fermor, L. L., What is laterite? Geol. Mag., vol. 8, 1911, pp. 454–462.

[591] Miller, W. G., Laterite ore deposits, Rept. Ontario Bureau of Mines, vol. 26, pt. i, 1917, pp. 3–19. Fox, C. S., Bauxite, London, 1927.

[592] Lacroix, A., Les latérites de la Guinée, Nouv. Arch. Nat. Hist., Paris, vol. 5, 1913, pp. 255–358 (260). See also Harrassowitz, H., Laterit, Fortsch. d. Geol. u. Pal., 1926, pp. 387–398.

[593] Holland, T. H., On the constitution, origin, and dehydration of laterite, Geol. Mag., vol. 50, 1913, pp. 59–69.

Maclaren considered that the production of laterite requires tropical heat and vegetation and alternating periods of dry and rainy weather. During the dry weather, moisture brought to the surface by capillary action evaporates and deposits any matter in solution in and on the surface materials, of which some may be replaced.[594] Mead suggested that the reduction of silicates to aluminum hydroxides requires the maintenance of an open texture in the clays, and that this depends on the absence of frost.[595] The presence of alkaline waters to leach out the silica would be a favorable factor. According to Maclaren, laterites form "only on level or approximately level surfaces," a view supported by Davis.[596] The thickness may attain to 50 or more feet.

The most important and best known occurrences of lateritic iron oxide of the western hemisphere are in Cuba, where such deposits are on plateau-like areas which extend over many thousands of acres and range up to about 50 feet in thickness.[597] Considerable alumina not combined with silica occurs with the hydroxide of iron and some magnetite seems to be present, for whose origin organic action is suggested. There seems to be general agreement that the deposits have resulted from the laterization of serpentine,[598] although it has been suggested that the deposits of the Camaguey district are mainly derived from limestone.[599] The large deposits are in the places of formation, but there are many local occurrences of which the materials have been transported from the original place of origin.

Among the best known and most important sedimentary deposits of iron oxides and hydroxides are the widely distributed bog and lake limonites, the Clinton hematites, the Ordovician Wabana hematites of Newfoundland, the Jurassic Minette limonites of France and western Germany, the Pre-Cambrian hematites of the Lake Superior region and Brazil, and the lateritic deposits of Cuba.

Bog limonites consist essentially of yellow to red or dark brown mixtures

[594] Maclaren, I. M., On the origin of certain laterites, Geol. Mag., vol. 43, 1906, pp. 536–537.

[595] Mead, W. J., Occurrence and origin of the bauxite deposits of Arkansas, Econ. Geol., vol. 10, 1915, pp. 22–54.

[596] Davis, W. M., Physiographic relations of laterite, Geol. Mag., vol. 57, 1920, pp. 429–431.

[597] Cumings, W. L., and Miller, B. L., Characteristics and origin of the brown ores of Camaguey and Moa, Cuba, Trans. Am. Inst. Min. Eng., vol. 42, 1911, pp. 116–137.

[598] Cumings and Miller, op. cit.; Spencer, A. C., Occurrence, origin and character of the surficial iron ores of Camaguey and Oriente Provinces, Cuba, Trans. Am. Inst. Min. Eng., vol. 42, 1911, pp. 103–109; Hayes, C. W., The Mayari and Moa iron-ore deposits of Cuba, Ibid., vol. 42, 1911, pp. 109–115; Weld, C. M., The residual iron ores of Cuba, Ibid., vol. 40, 1909, pp. 299–312.

[599] Leith, C. K., and Mead, W. J., Origin of the iron ores of central and northeastern Cuba, Trans. Am. Inst. Min. Eng., vol. 42, 1911, pp. 90–102.

of ferric hydroxide, iron silicate, iron sulphate, iron carbonate, organic material, and clay and sand. They are generally high in phosphate (iron phosphate, vivianite), and locally wad or bog manganese is abundant. Impressions of leaves and twigs are found in many places. Clay generally underlies a deposit, and the cover is earthy matter rich in humus or other organic matter. Where associated with abundant carbonaceous material, parts of the deposits, especially those near the base, may consist partly or wholly of siderite, supposed to have resulted from the deoxidation and carbonation of ferric hydroxide by decaying organic matter.

The deposits are in the form of layers of flat disk-like or irregular bodies, and they originate in shallow waters in which vegetation is abundant and into which streams carry iron. They may form on the surface of the bottom or beneath porous surface material resting on impervious material. According to Shaler, they are most abundant along the margins of water bodies and are wanting in the centers.[600] The layers may reach a foot in thickness, and they thin outward into deeper waters. In the shallow water the ore is frequently in concretionary form, and few concretions are found in waters of greater depth than 2 feet.[601] These range up to about a foot in diameter, and in most instances they appear to have formed around nuclei. In the deeper water the deposits consist of iron-bearing muds. In some Canadian and Swedish[602] lakes they form regularly, do not reach more than 1.6 feet in thickness, and consist of light ochreous mud containing vegetable débris. This hardens to a blackish, gray brownish, or greenish crust.

The Clinton type of iron sediments is represented by the Clinton hematites of the Appalachians, the Richmond hematites of eastern Wisconsin, the Minette deposits of the Jurassic of France and western Germany, and the Wabana deposits of Newfoundland.

The Clinton hematites of the Appalachians range in thickness from a few inches to 40 feet, and beds persist for many miles. The deposits are of three general classes: oolitic, fossil, and powdery granular hematite. Locally smooth and shiny-surfaced pebbles of hematite and hematite mixed with clay occur near the base. Similar smooth and shiny-surfaced pebbles occur at the base of the "Clinton" deposits near Iron Ridge, Wisconsin. The ores contain considerable calcium carbonate and silicon dioxide.

The fossil ores are replacements of fossil tests, among which those of bryozoa appear to dominate. Opinion differs with respect to whether the

[600] Shaler, N. S., 10th Ann. Rept. U. S. Geol. Surv., pt. i, 1890, p. 305.

[601] Harder, E. C., Iron-depositing bacteria and their geologic relations, Prof. Paper 113, U. S. Geol. Surv., 1919, p. 53.

[602] Beck, R., The nature of ore deposits, 1909, Transl. by Weed, W. H.

oolitic ores are replacements or original deposits. Many have been disposed to consider them original deposits or replacements shortly subsequent to deposition, whereas others assign them to replacement long after deposition;[603] the interpretation in each instance applying to some particular occurrence. The powdery and granular hematites may have originally been deposited in that form, or they may be of subsequent origin. It also seems possible, but hardly probable, that in some cases they may be lateritic soils. The waters of deposition of the original materials of the fossil ores and the oolites were undoubtedly shallow.

The Minette limonites of northeastern France and western Germany are near the base of the Dogger division of the Jurassic and are in the form of lenticular beds interstratified with shale, marl, and sandstone. The maximum number of beds bearing iron in significant quantity is seven; these range in thickness up to 20 feet and are distributed through a vertical distance of 75 to 150 feet. The limonite is oolitic, with the oolites about the dimensions of millet seed and consisting of ferric hydroxide with a skeleton of silica. Nuclei of the oolites range from organic fragments to mineral particles, and in some instances nuclei are fragments of oolites. The shapes tend to be ellipsoidal. They are cemented by silica, lime, or clay. It is generally held that the iron was deposited as original sediments,[604] but some, among whom is Cayeux,[605] have urged that they are replacements.

The beds in the Wabana hematites range in thickness up to 30 feet. The hematite in large part is oolitic, with the oolites having diameters ranging from 0.5 to 0.1 mm. and consisting generally of alternate layers of hematite and chamosite, although locally they may be entirely of hematite or chamosite. The matrix between the oolites is generally chamosite, but it may be hematite, quartz, or siderite, wholly or in part. No calcium carbonate is present, but there is abundant calcium phosphate. The marine fossils in the hematites suggest origin in a marine environment.[606] Similar

[603] Articles supporting the theory of original deposition or contemporaneous replacement are: Smyth, C. H., jr., On the Clinton iron ore, Am. Jour. Sci., vol. 43, 1892, pp. 487–496; Burchard, E. F., The Clinton iron ore deposits in Alabama, Trans. Am. Inst. Min. Eng., vol. 40, 1909, pp. 75–133; Newland, D. H., The Clinton iron ore deposits in New York State, Ibid., vol. 40, 1909, pp. 165–183; Eckel, E. C., Ores, fuels, and fluxes of the Birmingham District, Alabama, Bull. 400, U. S. Geol. Surv., 1901, pp. 28–39. An article supporting the theory of subsequent replacement is: Rutledge, J. J., The Clinton iron ore deposits in Stone valley, Huntingdon County, Pa., Trans. Am. Inst. Min. Eng., vol. 40, 1909, pp. 134–164.

[604] Berg, G., Über die Structur und Entstehung der lothringischen Minetteerze, Zeits. d. deut. geol. Gesell., vol. 73, 1922, pp. 113–136, Pl. 5. See papers cited by Berg.

[605] Cayeux, L., Les minérais de fer oolithique de France, I. Minérais de fer primaires, Paris, 1909; II. Minérais de fer secondaires, Paris, 1922.

[606] Hayes, A. O., Wabana iron ore of Newfoundland, Mem. 78, Geol. Surv. Canada, 1915.

iron sediments are the ferric chamosite oolites of the Jurassic Frodingham ironstone of England.[607]

The Lake Superior hematites are associated with much chert, iron silicate, iron carbonate, and other substances. Because of the large quantity of iron in these Pre-Cambrian sediments and the assumed rapid deposition, it has been thought that a source other than the ordinary one of weathering must have been responsible for the iron-bearing solutions from which the iron-bearing sediments were precipitated. This source has been sought in magmatic waters derived from lavas extruded on, or adjacent to, the bottoms of the water bodies in which deposition took place, or magmatic waters reaching the surface in hot springs.[608] The relative rarity of contemporaneous igneous rocks in association with the iron formation in some localities offers a possible difficulty for the former theory. It may be that the explanation of magmatic waters reaching the surface as springs is more in harmony with the facts, and that these springs may have been forerunners of the Keweenawan volcanoes, the lavas at the time of deposition of the iron rising toward the surface and being preceded by waters emanating from them. These waters are thought also to have carried large quantities of silicon which was precipitated as iron silicate, quartz, etc. A theory of this type has been proposed by Davis and Lawson to explain cherts of the California Franciscan formation;[609] and Collins, Quirke, and Thomson[610] have explained the iron formations of the Michipicoten Iron Ranges as having been "formed by ascending heated mineralized waters at many loci in a land area of great volcanic activity," the loci ranging in area from a few yards to 7 or 8 miles in major horizontal extent. The waters are assumed to have been hot and mineralized with carbon dioxide, iron, silica, sulphur compounds, and perhaps other substances. If the waters were highly heated, their deposits cannot be considered sediments, but as the iron formations have considerable to large distribution, it seems probable that cooling to temperatures normal to the surface would have taken place before transportation had extended far. In general, the facts relating to

[607] Hallimond, A. F., Iron ores: bedded ores of England and Wales, Mem. Geol. Surv. Great Britain, Min. Res., vol. 29, 1925. Hallimond's work is devoted to the petrography and chemistry of the ores. For other works discussing the British sedimentary iron deposits there should be consulted Lamplugh, G. W., Wedd, C. B., and Pringle, J., Bedded ores of the Lias, Oolites and later formations of England, op. cit., vol. 12, 1920, and Strachan, A., Gibson, W., Cantrill, T. C., Sherlock, R. L., and Dewey, H., Pre-Carboniferous and Carboniferous bedded ores of England and Wales, op. cit., 1920.

[608] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior Region, Mon. 52 U. S. Geol. Surv., 1911, pp. 506–516.

[609] Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. California Publ., Dept. Geol. vol. 11, 1918, pp. 235–432.

[610] Collins, W. H., Quirke, T. T., and Thomson, E., Michipicoten Iron Ranges, Mem. 147, Geol. Surv. Canada, 1926, pp. 50–78.

the Lake Superior and similar iron formations are in harmony with the interpretation of a magmatic source, for the quantity of iron and silica do not seem to fit in well with any other theory.

Gruner[611] has presented evidence suggesting that the iron of the Archean Biwabik formation was produced, transported, and deposited by the ordinary agents of weathering, transportation, and deposition. Gruner infers that the Keewatin vulcanism had covered large parts of North America with greenstone and basalt, that a warm humid climate prevailed, that abundant vegetation of low forms aided in the decay of the rocks and placed silica and iron in transportation in large quantities, and that these were held in stable form through the presence in the water of protective organic colloids. The suspended, non-colloidal material is supposed to have been largely deposited in deltas, while the stable colloids of iron and silica were carried to clear but shallow waters, where they are supposed to have been deposited mainly through the agency of bacteria and algæ. Exceptional conditions, such as changes in the coast lines and large floods, occasionally brought mechanically transported sediments to the places where the iron and silica were being deposited. Various iron silicates developed, and some of the colloidal precipitates took the sphærulitic or oolitic form. Due to the presence of so much organic matter, most of the carbonates other than iron were held in solution. An atmosphere rich in carbon dioxide would have assisted in preventing deposition of these carbonates.

Gruner's theory suggests that the conditions necessary for relatively pure deposits of silica and iron are functions of the character of the rocks eroded, the topography, climate, and vegetation of the regions undergoing erosion, and the shallowness and extent of shallowness of the water bodies in which deposition was taking place. Granted that iron and silica were brought to the water bodies in sufficient quantities in stable form, that the mechanical sediments were held adjacent to the shore, and that the waters were rich in organic matter and swarming with bacteria, there would have been a steady but slow accumulation of silica and iron. This deposition might have been interrupted from time to time as great storms swept mechanical sediments over the sites of silica and iron deposition, and interrupted on a wider scale by deepening of waters through advances of shoreline landward, thus limiting the plant growth and leading to the precipitation of calcareous matter, or by retreat of the shoreline seaward, thus bringing the sites of mechanical deposition to those previously given to the deposition of silica and iron.

The hematites of the state of Minas Geraes in southeastern Brazil consist

[611] Gruner, J. W., Origin of sedimentary iron formations, etc., Econ. Geol., vol. 17, 1922, pp. 407–460.

of an iron-oxide-bearing quartzite known as itabirite in which are lenses and beds of ferruginous schist and pure hematite. The iron-bearing formation ranges in thickness from less than 20 to more than 4000 feet, with beds of hematite 2000 feet thick containing 65 per cent metallic iron. No contemporaneous igneous rocks are associated with the ores, and they are believed to have resulted from normal processes of sedimentation and to have been deposited by chemical and biological agencies at the same time as the associated detrital materials. The hematites are of two kinds, bedded and fragmental, the latter washed from the former.[612]

Iron Carbonate

Iron carbonate occurs in the form of beds and lenses and is usually associated with limestones and shales. There are four general types: (a) the concretionary ironstone type; (b) the black band type, represented by the black band ores of the Coal Measures; (c) the block ore type; and (d) the limestone type.

The concretionary ironstone beds, or kidney ores, as they are sometimes designated, consist of rounded and kidney-shaped concretions of iron carbonate ranging in diameter up to 12 or more inches. The concretions are embedded in shale or clay, either of which is likely to be more or less carbonaceous. They consist of impure iron carbonate, the impurities commonly being clay, calcium carbonate, and other substances. In some cases impure iron carbonate and clay or lime form concentric bands in the concretions. In some occurrences a concretionary zone passes laterally into a bed, of which the top commonly may be cut by cracks.[613] The black band iron carbonate occurs interbedded in shales and clays, beds ranging to a half dozen or more inches in thickness. The name arises from the presence of bituminous or carbonaceous matter, giving the black color. Block ore is found in distinct beds of small but fairly uniform thickness interbedded with sandy shales or clays. The iron carbonate generally contains more or less sand. Limestone iron carbonates are usually in thicker but more irregular beds than other varieties; they are found at or near the tops of limestone formations and are believed to have originated for the most part from the replacement of limestone by iron derived from overlying formations. The limestone type has the greatest commercial importance.

Besides the above four common types of sedimentary iron carbonate deposits, there are the oolitic siderites and compact chamosites of the

[612] Leith, C. K., and Harder, E. C., Hematite ores of Brazil and a comparison with hematite ores of Lake Superior, Econ. Geol., vol. 6, 1911, pp. 670–686.

[613] Lucas, J., On the origin of clay-ironstone, Quart. Jour. Geol. Soc., vol. 29, 1873, pp. 363–369.

Cleveland Hills and other parts of England in the Jurassic,[614] and the somewhat unusual type known as cherty iron carbonate which occurs abundantly in the Lake Superior iron formations. The latter is often found in places where the iron-bearing formations have been protected from oxidation, and this has suggested that the original form in which much of the Lake Superior ores were deposited was iron carbonate. This cherty iron carbonate is light grayish, brownish, or greenish in color, and fine-grained. It consists of alternating fine laminæ of chert and iron carbonate, the laminæ in many places being very regular and having considerable extent. In some localities shaly or slaty material largely takes the place of chert.

The iron to form the carbonates is assumed to have been brought to the places of deposition in solution in the form of ferrous bicarbonate. The latter is supposed to be precipitated from solution through depletion of carbon dioxide under conditions which do not allow its replacement by oxygen. Such conditions are thought to obtain in the marshes and shallow waters of lakes, rivers, and the sea, where the photosynthesis of vegetation extracts the carbon dioxide from the water and the decay of organic matter uses up the oxygen. Any iron in the hydroxide form could also be reduced to the carbonate in the decaying organic matter in accordance with the reactions expressed by the two following equations:

$$2Fe_2O_3 \cdot 3H_2O + C = 4FeO + CO_2 + 3H_2O$$
$$4FeO + 4CO_2 = 4FeCO_3$$

Iron carbonate may also be precipitated by calcium carbonate reacting with ferrous sulphate in solution according to the equation:

$$FeSO_4 + CaCO_3 = FeCO_3 + CaSO_4$$

Most of the sedimentary iron carbonate beds found in various parts of the world appear from the associations to have been formed in the environments postulated. As most of the reactions take place under conditions where other sedimentary material is abundant, it follows that iron carbonate deposits are rarely pure or extensive. They are usually mixed with organic matter, clay, sand, lime carbonate, lime sulphate, manganese carbonate, magnesium carbonate, silicon dioxide, etc.

It has been suggested that some of the iron carbonate of the Lake Superior region might have developed from the contact of carbon dioxide, either hot or cold, with greenalite, the carbon dioxide being derived from vegetable matter in the waters, from carbonaceous sediments penetrated by the mag-

[614] Hallimond, A. F., Iron ores: Bedded ores of England and Wales; Mem. Geol. Surv., Gr. Br., Min. Res., vol. 29, 1925.

mas or solutions responsible for the greenalite, or from the volcanic material itself. The equation[615] expressing the reaction is as follows:

$$FeSiO_3 + CO_2 = FeCO_3 + SiO_2$$

As free oxygen does not appear to be present in volcanic emanations, in the cavities of igneous rocks, or in meteorites,[616] while carbon dioxide is present in each, Lane[617] and others have suggested that the Keewatin and Huronian atmospheres were largely composed of carbon dioxide. MacGregor has emphasized the low oxidation of the Rhodesian early Pre-Cambrian rocks as evidence supporting the suggestion; and finds that they are characteristically low in the ferric oxide of iron and contain no evidence of contemporaneous oxidation, and hence considers that the Pre-Cambrian banded iron deposits of worldwide distribution are explicable if the atmosphere of their times of origin lacked oxygen and was rich in carbon dioxide. As a consequence of such an atmosphere, all waters would have been charged with carbon dioxide and extremely low or wanting in oxygen. Iron salts would have very readily been transported in solution as ferrous bicarbonate and could not easily have been oxidized and precipitated as the hydroxide, but more commonly would have been deposited as carbonate, sulphate, silicate, chloride, or some other iron salt. Likewise, weathering would cause other elements to form carbonates, chlorides, sulphates, silicates, but rarely oxides. There would thus be brought in solution to the sites of deposition large quantities of iron, calcium, and magnesium in the form of bicarbonates. The iron would have been deposited first, while the high carbon dioxide content of the waters would lead to the retention in solution of the calcium and magnesium carbonates until plants appeared to release oxygen from the carbon combination and fix the carbon in the rocks, and animals and plants began to utilize calcium and magnesium for shell structures. This theory explains the general absence of limestones in the early Keewatin. The advent of plant life in the late Keewatin or early Huronian would have rapidly released oxygen from carbon dioxide and fixed carbon in the deposits. This lowering of the carbon dioxide content of the atmosphere, and ultimately of the waters would have resulted in the precipitation

[615] Van Hise and Leith, Geology of the Lake Superior region, Mon. 52, U. S. Geol. Surv., 1911, p. 526.

[616] Chamberlin, R. T., The gases in rocks, Jour. Geol., vol. 17, 1909, pp. 534–568.

[617] Lane, A. C., Lawson's correlation of the Pre-Cambrian Era, Am. Jour. Sci., vol. 43, 1917, pp. 42–48. Barrell, J., in The evolution of the earth and its inhabitants, 1919, p. 44. MacGregor, A., The problem of the Pre-Cambrian atmosphere, South African Jour. Sci., vol. 24, 1927, pp. 155–172. T. T. Quirke, in a review of MacGregor's article, takes exception to certain of the assumptions: Origin of sedimentary iron ores, Econ. Geol., vol. 20, 1925, pp. 770–771.

of the calcium and magnesium carbonates held in solution, thus forming the great Huronian dolomite and dolomitic limestone formations.

Iron Sulphides

Iron sulphide in the form of nodules, lenses, and beds of pyrite and marcasite occurs in clays and shales and is particularly common in black shales and some coal beds, forming the "coal brass" of the latter. Small particles of pyrite and marcasite are common in many limestones and sandstones. Melnikovite, the black disulphide of iron, is largely confined to Tertiary and Recent sediments. It is thought ultimately to change to pyrite or marcasite and in turn to form from ferrous monosulphide. Black muds, whose color is partly or largely due to ferrous disulphide, are being deposited at the present time in lagoons and other waters with poor circulation in many parts of the world, notably the Black Sea and the limans of the east Baltic, and it seems to be a constituent of, and to be partly responsible for, the colors of the blue and gray muds which have extensive distribution over large areas of the present ocean floor.

Pyrite layers, lenses, and nodules of sedimentary origin occur in rocks as old as the early Paleozoic. Beds range from less than an inch to 10 or more feet in thickness. In the Wabana hematite beds of Newfoundland occur oolitic pyrite beds, separated by fissile black shales, the pyrite beds ranging in thickness from an inch to a foot. The beds thicken and thin, but are persistent, and a marine origin is suggested by the presence of marine fossils.[618] Similarly distinctly stratified thin layers occur in the Devonian of Westphalia at Metten on the Lenne, where they average about 10 feet thick and consist of pyrite and barite. The pyrite is said to be partly oolitic.[619] It is possible that these examples have resulted from replacement.

The black disulphide, melnikovite, is magnetic. It occurs finely disseminated and as streaks, thin layers, and nodules in Miocene brown clay in the Government of Samara, Russia. The nodules have spherical, oval, grape-like, and kidney shapes, concentric structure, and rarely exceed 1 mm. in diameter. The particles are somewhat impure in that they contain quartz, calcite, clay, and flakes of muscovite. Pyrite is associated.[620]

According to Newhouse,[621] the iron sulphide of coal beds in the form of

[618] Hayes, A. O., Wabana iron ores of Newfoundland, Mem. 78, Geol. Surv. Canada, 1915, p. 15.

[619] Harder, E. C., Iron depositing bacteria and their geologic relations, Prof. Paper 113, U. S. Geol. Surv., 1919, p. 61.

[620] Harder, E. C., op. cit., p. 62.

[621] Newhouse, W. H., Some forms of iron sulphide occurring in coal and other sedimentary rocks, Jour. Geol., vol. 35, 1927, pp. 73–83.

bands or layers is chiefly marcasite, whereas concretions along stratigraphic bands in other sedimentary rocks are chiefly pyrite. Newhouse considered each contemporaneous in origin with the enclosing rocks and to have been deposited as colloidal jels. He states that concretions usually have two zones: an inner of fine-grained, more or less equi-dimensional crystals, and an outer in which the crystals are radially elongated; the outer termini of the latter may have crystal faces.

Doss[622] explains the origin of sedimentary deposits of iron sulphide as follows: Iron is carried in solution to waters where organic matter is abundant. Here the iron is precipitated, either directly as black colloidal hydrous ferrous sulphide by reaction with hydrogen sulphide liberated by bacteria from decaying organic matter; or as ferric hydroxide by iron bacteria, which in the presence of hydrogen sulphide under reducing conditions is changed to hydrated ferrous monosulphide. By loss of water and the addition of sulphur present in the mud, the latter is changed to melnikovite, which gradually alters to pyrite as the enclosing mud becomes consolidated. It has been shown by van Delden[623] that the muds on the bottoms of canals on the Dutch coast, which to a depth of many meters are blackened by iron sulphide, owe the production of the sulphide to bacterial reduction of sulphates, through which hydrogen sulphide is produced, and this, reacting with iron salts in the muds, produces the iron sulphide and the black color. According to Harder, ferrous sulphide may be formed in four distinct ways.[624] (a) Hydrogen sulphide formed by the decomposition of sulphur-bearing proteins under the action of decay-producing bacteria may react upon ferrous salts in solution, forming ferrous sulphide. This is probably a common manner of formation. (b) Certain bacteria, as *Vibrio hydrosulfureus* and *Bacterium hydrosulfureum ponticum*[625] of the Black Sea, known as sulphate reducers, have the ability, in the presence of decaying organic matter, to take oxygen from sulphites, sulphates, and thio-sulphates, and to form sulphides. (c) If the sulphides thus formed are other than iron sulphide, they may react with carbon dioxide and water to form hydrogen sulphide, which in turn reacts with ferrous salts in solution to form ferrous sulphide. (d) Some bacteria in the presence of decaying organic matter may act directly on free sulphur to form hydrogen sulphide, which acts upon ferrous

[622] Doss, B., Melnikowit, ein neues Eisenbisulfid, und seine Bedeutung für die Genesis der Kieslagerstätten, Zeits. Pract. Geol., Jahrg. 20, 1912, pp. 453–483 (460–461).

[623] van Delden, A., Beitrag zur Kenntnis der Sulfatreduction durch Bacterien, Centralbl. f. Bacteriologie, Abt. 2, vol. 11, 1903–04, pp. 81–94, 113–119.

[624] Harder, E. C., op. cit., p. 41.

[625] Referring to Issatchenko, Bastin states that this identification is doubtful, and that the common form is *Microspira aestuarii*, Bastin, E. S., The problem of the natural reduction of sulphates, Bull. Am. Assoc. Pet. Geol., vol. 10, 1926, pp. 1270–1299 (1278). This is a valuable paper and should be consulted by those interested.

salts in solution, forming ferrous sulphide. Bacteria of the following species: *Vibrio hydrosulfureus*, *V. thermodesulfuricans*,[626] *Bacterium hydrosulfureum ponticum*, *Proteus vulgaris*, *Bacillus mycoides*, *Spirillum desulfuricans*, *Microspira æstuarii*, and *Bacterium sulfureum*, are known to have the the ability to reduce sulphates, and some of them can reduce thio-sulphates. Another group of bacteria has the ability to oxidize hydrogen sulphide to free sulphur and sulphuric acid, the latter immediately uniting with the bases present to form sulphates. These bacteria belong to the colorless members of *Thiothrix* and *Beggiatoa* and the red or violet colored varieties known as the Rhodobacteria. These bacteria require both hydrogen sulphide and oxygen, and as increase of hydrogen sulphide in solution results in expulsion of oxygen, there is a certain horizon in the water where the two substances, oxygen coming from the upper waters and hydrogen sulphide

Surface of the water

$\downarrow$ $\downarrow$ $\downarrow$

Oxygen diffusing from the air into the water

$\downarrow$ $\downarrow$ $\downarrow$

Level of optimum conditions for hydrogen-sulphide-consuming bacteria and the formation of sulphur and sulphuric acid

$\uparrow$ $\downarrow$

$\uparrow$ $\downarrow$ Sulphur and sulphates settling to the bottom and hydrogen $\downarrow$ $\uparrow$ sulphide rising

$\uparrow$ $\downarrow$

Vicinity of the bottom and in the bottom deposits with sulphate-reducing and hydrogen-sulphide-forming bacteria.

FIG. 60. DIAGRAM ILLUSTRATING THE CYCLE OF CHANGE DUE TO DIFFERENT SULPHUR BACTERIA

from the bottom, are both present in the best proportions for their optimum activity. This level contains the greatest abundance of the hydrogen-sulphide-consuming bacteria, whereas below that level the sulphate-reducing and hydrogen-sulphide-forming bacteria to which free oxygen is not essential are most active.[627] The cycle of change is expressed in the diagram (fig. 60).

According to Reed,[628] the hydrogen sulphide is formed by bacteria from proteins containing sulphur. This unites with iron to form the black sulphide of iron only in a neutral or basic solution. The same reaction responsible for the hydrogen sulphide is said also to produce ammonia or other bases, so that the surrounding medium may be alkaline. However, it seems

[626] Elion, L., A thermophilic sulphate-reducing bacterium, Centralb. f. Bacteriologie, Abt. 2, vol. 63, 1924–25, pp. 58–67.

[627] Harder, E. C., op. cit., pp. 41–44.

[628] Reed, G. B., in Kindle, E. M., Notes on the tidal phenomena of Bay of Fundy rivers, Jour. Geol., vol. 34, 1926, pp. 651–652.

to be known that proteins are not essential for the production of hydrogen sulphide.

The character of the medium and the temperature seem to determine the form of the iron sulphide which forms, the former being the more important. Marcasite forms in an acid solution, pyrite in a neutral or slightly acid solution, and melnikovite in an alkaline solution. The optimum conditions for marcasite were found by Allen, Crenshaw, and Johnston[629] to exist in a solution containing 1.18 per cent free sulphuric acid at 100°C. Decrease in acidity reduces the formation, and a change of temperature in either direction works to the same end. Decrease of acidity to neutrality and raising the temperature favors deposition of pyrite. Melnikovite seems to form best at temperatures below 100° C., but it may form at 100° C. in alkaline solutions.[630] Variation in the character of a medium would thus lead to alternations in the deposition of the three sulphides.

Iron Silicates

The common silicates of iron are greenalite, chamosite, berthierite, and glauconite.

Greenalite occurs as dark green spherules which are homogeneous and amorphous. The spherules have a maximum diameter of about a millimeter, and the shapes range from ellipsoidal to irregularly rounded. They are commonly imbedded in a matrix of chert. The substance has the composition of $FeMg(SiO_2) \cdot nH_2O$.

Greenalite is considered one of the original substances from which the iron ores of the Lake Superior region were derived, and it is believed to have been formed by the action of alkaline silicates on ferrous salts. Without the magnesium, it has been formed in the laboratory by Mead through the reaction of ferrous salts and water glass in saline solution. The composition varies somewhat with the temperature of the water, and whether the ferrous salts or the water glass are in excess. The salts used in the experiments were $FeCl_2$ and $FeSO_4$. The equations[631] expressing the reactions are as follows:

$$FeSO_4 + Na_2O \cdot 3SiO_2 = FeO \cdot 3SiO_2 + Na_2SO_4$$
$$FeCl_2 + Na_2SiO_3 = FeSiO_3 + 2NaCl$$

The material formed was in the nature of a green flocculent precipitate which on drying had a granular texture and optical properties similar to the

[629] Allen, E. T., Crenshaw, J. L., and Johnston, J., The mineral sulphides of iron, Am. Jour. Sci., vol. 33, 1912, pp. 169–236.

[630] Tarr, W. A., Alternative deposition of pyrite, marcasite, and possibly melnikovite, Am. Min., vol. 12, 1927, pp. 417–422.

[631] Van Hise and Leith, Geology of the Lake Superior Region, Mon. 52, U. S. Geol. Surv., 1911, pp. 521–522.

greenalite found in the Mesabi rocks. The fact that an alkaline silicate rather than free silicic acid was required for its formation makes it necessary to account for the occurrence of this substance in any possible original solution in case it is postulated that the greenalite was formed in the same way in the laboratory. This is not a difficulty, as sodium silicate is one of the common products of weathering and is formed where sea water comes in contact with lavas or the hot solutions emanating therefrom.[632]

Chamosite is green to gray in color and is generally of concentric structure. Berthierite is very similar in structure, appearance, and composition. Both are magnetic, the former very feebly, the latter strongly. Each is a ferrous silicate with alumina and water, iron carbonate and other iron silicates being common associates. Chamosite occurs as an important constituent in the Wabana iron deposits of Newfoundland and the Jurassic iron ores of the Cleveland Hills of England, and it forms part of the Minette ores. The manner of origin is not entirely clear, but Hallimond assigns it to direct chemical precipitation. He gives its composition as $2SiO_2 \cdot Al_2O_3 \cdot 3FeO \cdot Aq$ with some Fe_2O_3 replacing the alumina and some magnesium replacing the ferrous iron.[633]

Glauconite, an essential constituent of greensand, occurs distributed through rocks of all geologic ages from early Paleozoic to Recent, and it is known to be forming on the ocean floor in many places at the present time. Extensive deposits are in the Upper Cambrian of Wisconsin, the Silurian of Bohemia, the Jurassic of Europe, the Cretaceous of New Jersey, the Upper and Lower Cretaceous of the London and Paris basins, the Tertiary of many localities, and it is probably present in every system beginning with the Cambrian. It may form beds which are almost pure, but more commonly it occurs as a major or minor constituent of limestone, sandstone, and marl. Glauconite may occur throughout an entire formation or be confined to a single layer or group of layers. Thus, in the Cambrian Franconia-Mazomanie formation of western Wisconsin there are two glauconite-containing units, each 25 to 30 feet thick. Goldman[634] has directed attention to the occurrence of glauconite in the "Bend Series" of Texas in connection with stratigraphic breaks, and has shown that many significant breaks are indicated by the occurrence of autochthonic glauconite, and, in many instances, of phosphate also, directly above the break or rarely more than a foot or two above, the two substances usually being associated with

[632] Van Hise and Leith, op. cit., pp. 521–525.

[633] Hallimond, A. F., Iron-ores: Bedded ores of England and Wales, Mem. Geol. Surv. Gr. Br., Min. Res., vol. 29, 1925.

[634] Goldman, M. I., Jour. Washington Acad. Sci., vol. 60, 1919, p. 502. Lithologic subsurface correlation in the "Bend Series" of North Central Texas, Prof. Paper 129-A, U. S. Geol. Surv., 1921. Basal glauconite and phosphate beds, Science, vol. 56, 1922, pp. 171–173.

quartz sands. The glauconite in association with a break is usually more abundant, predominantly more coarse, of deeper color, and of more irregular shapes than that occurring elsewhere in the formation.

Glauconite is not known to originate in sediments other than marine. Its absence in typical fresh-water sediments may be explained on the basis of the abundance of reducing environments in the deep fresh-water basins because of the presence of much organic matter and perhaps due to scarcity of potash in fresh water.[635]

Glauconite occurs in sediments as irregularly shaped particles with botryoidal surfaces, as spherical particles, and as fragments ranging to microscopic dimensions. Maximum diameters approximate about 1 millimeter. Particles with botryoidal surfaces may represent original shapes of formation. Spherical particles may have developed from the former by abrasion, although this seems doubtful in some cases, and the small fragments may also be products of abrasion, although this, also, is open to question (fig. 61). None of the particles has concentric—concretionary or oolitic—structure.

Pure glauconite is said to have the symbol of $FeK \cdot Si_2O_6 \cdot nH_2O$, but it is commonly impure, and the place of the iron may be taken by aluminum, and other bases may replace a part of the potassium. Schneider gives the formula of $(K \cdot Na)\ (Fe \cdot Mg)\ (Fe \cdot Al)_3Si_6O_{18} \cdot 3H_2O$.[636] This differs from the formula commonly given in the presence of ferrous iron and the statement of a definite quantity of water. Ross[637] expressed the view that glauconite represents a series having the expression of $R_2O{:}RO{::}R_2O_3{:}SiO$, one extreme having the substances represented by the symbols in the proportion of 1:2::2:10 and the other of 1:1::3:10, R representing the substances shown in the formula above. The mineral is crystalline, but the crystal form, which is probably monoclinic, is rarely shown.

The mineral celadonite, stated to form as a decomposition product of augite, has the same color as glauconite. Von Gümbel and Glinka[638] considered it chemically identical with glauconite.

Table 59 gives (1) the mean of four analyses of modern glauconites collected by the Challenger expedition,[639] (2) the mean of four analyses of

[635] Caspari, W. A., Contributions to the chemistry of submarine glauconite, Proc. Roy. Soc., Edinburgh, vol. 30, 1910, pp. 364–373. Murray, J., and Philippi, E., Die Grundproben der "Deutschen Tiefsee-Expedition," vol. 10, pt. iv, Wissenschaftliche Ergebnisse der Deutschen Tiefsee-Expedition, 1908, pp. 156–157, 175–180. Collet, L. W., and Lee, G. W., Recherches sur la glauconie, Proc. Roy. Soc., Edinburgh, vol. 26, 1906, pp. 238–278; Sur la composition chimique de la glauconie, Compt. Rend. Acad. Sci. Paris, vol. 142, 1906, pp. 999–1001.

[636] Schneider, H., A study of glauconite, Jour. Geol., vol. 35, 1927, pp. 289–310.

[637] Ross, C. S., The optical properties and chemical composition of glauconite, Proc. U. S. Nat. Mus., vol. 69, 1926, pp. 1–15.

[638] Quoted by Clarke, F. W., op. cit., p. 522.

[639] Quoted by Clarke, F. W., op. cit., p. 522.

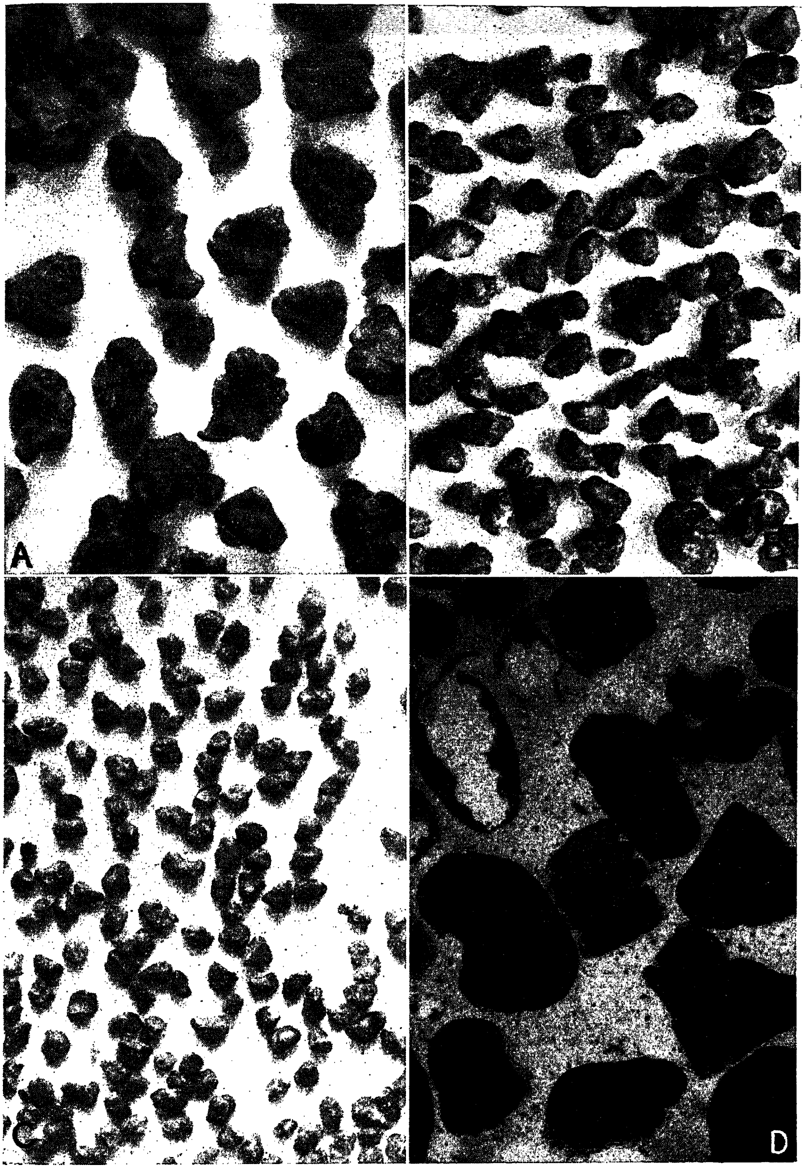

FIG. 61. MICROPHOTOGRAPHS OF NEW JERSEY GLAUCONITE

A, grains between $\frac{1}{10}$ and $\frac{1}{20}$ inch in diameter, maximum dimensions, × 10, showing characteristic shapes. *B*, grains between $\frac{1}{20}$ and $\frac{1}{40}$ inch, × 10, shapes similar to those of *A* but more worn. *C*, grains between $\frac{1}{40}$ and $\frac{1}{60}$ inch, × 10, shapes similar to those of *A* and *B* but considerably more worn. *D*, thin section of glauconite grains between $\frac{1}{40}$ and $\frac{1}{60}$ inch, ×50, showing the flaky to granular structure of glauconite and in the center a supposed crystal with rude cleavage. Photograph by C. R. Mansfield, U. S. Geol. Surv.

celadonites collected in Scottish localities, (3) an analysis of purified Cretaceous glauconite from New Jersey,[640] and (4) an analysis of purified glauconite from the waters of the coast of Sussex, England.[641] Numbers 1 and 2 show the differences in the chemical composition of glauconite and celadonite with respect to aluminum, iron, magnesium, and potassium.

With most glauconite deposits there are associated other minerals and substances of which the most important are quartz, white mica, clay, feldspar, hornblende, magnetite, garnet, epidote, and shell and rock fragments. Quartz sand in the New Jersey greensands ranges from nothing to 50 per cent,[642] and the quartz sands in the Cambrian greensands of the upper Mississippi Valley range from about 10 to nearly 100 per cent. Phosphate concretions seem commonly to be present, having thus been found by the

TABLE 59

	1	2	3	4
	per cent	*per cent*	*per cent*	*per cent*
SiO_2	53.61	54.84	49.47	48.12
Al_2O_3	9.56	3.52	5.59	9.60
Fe_2O_3	21.46	12.64	19.46	19.10
FeO	1.58	4.90	3.36	3.47
MnO	Trace	0.24	P_2O_5 1.06	
MgO	2.87	6.65	3.96	2.36
CaO	1.39	0.89	0.60	0.76
K_2O	3.49	7.00	8.04	7.08
Na_2O	0.42	0.39	0.16	0.22
H_2O	5.96	9.62	8.54	10.06
CO_2			0.56	
	100.34	100.69	100.80	100.77

Challenger, Gazelle, Valdivia, and other expeditions. Collet states that zircon, tourmaline, and feldspar are commonly present.[643] Calcite appears to be invariably present, the particles in most cases seeming to be fragments of shells.

Modern glauconite appears to form in waters which are little shallower than 250 feet, the most favorable depth seeming to be near the 100-fathom

[640] Mansfield, G. R., Potash in the greensands of New Jersey, Bull. 727, U. S. Geol. Surv., 1922, p. 128.

[641] Hallimond, A. F., Mineralogical Magazine, vol. 19, 1922, p. 30; analysis by E. G. Radley.

[642] Prather, J. K., The Atlantic Highland section of the New Jersey Cretacic, Am. Geol., vol. 36, 1905, p. 167.

[643] Collet, L. W., Les dépôts marins, 1908, pp. 155–157.

line, but it is certain that the ancient glauconites, at least in many cases, were formed in much shallower waters, as some of the Cambrian glauconite beds of the upper Mississippi Valley are mud-cracked, and evidence of shallow waters is a characteristic of many formations of which glauconite is a constituent. However, it does not necessarily follow that the places of occurence of glauconite are the places of formation, as the particles are of low specific gravity and may thus be transported by currents of low competency. Glauconite seems to be forming at the present time on bottoms with depths ranging from 82 meters on the west coast of Africa to 3512 meters in the Indian Ocean.[644] It seems to be absent or relatively rare toward the centers of the ocean basins, but in the present deposits of the sea, greensands and green muds, the green arising from glauconite, cover an area of 1,000,000 square miles.[645] Glauconite does not seem to form where terrigenous sediments are present in large quantity, as near the mouths of rivers; neither does it apparently form where vegetable growth is abundant, although some organic matter seems to be necessary for development. The environments favoring the formation of glauconite seem to be fairly shallow, warm bottoms on which deposition is very slow, where there is considerable organic matter, and where any sediments which are deposited are subjected for a long time to the action of the sea water.[646] This environment must not be strongly reducing, as such yield iron sulphides, nor strongly oxidizing so as to form hydrous iron oxides. Some intermediate position seems essential. Bottoms seemingly very favorable for the formation of glauconite are those on the Agulhas Bank, where depths range between 50 and 150 meters, and the bottoms of the same depth surrounding tropical and warmer parts of the continental areas and upon which deposits of terrigenous sediments are small.

Opinion is not uniform with respect to the origin of glauconite. According to Murray and Renard,[647] the shells of foraminifera, and rarely those of other organisms, become filled with mud and organic matter, the latter in part derived from without and in part from the organisms to which the shells belonged. The decay of this organic matter transforms the iron in the mud into the sulphide, whose oxidation releases the sulphur. From the latter, sulphuric acid is formed, which decomposes the fine clay in the mud, setting free colloidal silica. The alumina is then removed in solution, leaving ferric hydroxide and colloidal silica, and the potash is

[644] Collet, L. W., op. cit., p. 188.

[645] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, p. 240.

[646] See in this connection, Goldman, M. I., General character, mode of occurrence and origin of glauconite, Jour. Washington Acad. Sci., vol. 9, 1919, p. 502.

[647] Murray, J. and Renard, A. F., op. cit. 1891, p. 389.

extracted from the water. Goldman has called attention to the virtual certainty that the formation of sulphuric acid would lead to the disappearance of the foraminiferal shell.[648] According to this explanation, the two necessary conditions for the formation of glauconite are foraminifera and mud.[649] Collet's[650] explanation of origin, on the other hand, is somewhat different. According to him, decaying organic matter acts on calcium or other sulphates in solution in the sea water, reducing them to sulphides, which then react with carbon dioxide and water to form hydrogen sulphide. As previously pointed out, bacteria are probably an important agent in the formation of hydrogen sulphide. The hydrogen sulphide unites with any iron oxide which may be present in the sediments, forming ferrous sulphide and sulphur. The sulphide is supposed to react with colloidal matter in clay, and water and potash are supposed to be derived from the sea water. He distinguishes three stages in the formation: in the first the particles consist of pellets representing the fillings of small shells, these fillings being largely or wholly composed of finely divided clay; in the second stage the pellets change color to brown, with progressive elimination of alumina and its replacement by ferric oxide; potash and water are introduced in the third stage, and the acquirement of the former is thought to continue somewhat indefinitely. Glauconite in the older geologic systems thus should be higher in potash than those of recent origin. This has been stated to be the case,[651] but the statement is not confirmed by the work of Schneider,[652] who states that the generalization has resulted from faulty analyses. Cayeux[653] has stated that organic matter is not essential to the formation of glauconite and that some glauconite seems to have formed without intervention of such.

Although there may be some connection between shells, particularly those of foraminifera, and modern glauconites, it is difficult to find much evidence therefor in the glauconite of the geologic column. Thousands of glauconite particles from the Cambrian of the upper Mississippi Valley, the Comanchean of Kansas, the Pennsylvanian of Texas, and other ancient formations have been studied by many students, and not a single particle seems to have been identified as proving connection with foraminiferal shells. Dryden states that the glauconite of the Miocene Calvert occurs only in foramini-

[648] Goldman, M. I., Maryland Geol. Surv., Upper Cretaceous, 1919, p. 170.
[649] Clark, W. B., Jour. Geol., vol. 2, 1894, p. 169.
[650] Collet, L. W., op. cit., pp. 132, 176.
[651] Collet. L. W., op. cit., p. 107; Cayeux, L., Introduction à l'étude pétrographique des roches sédimentaires, Mém. Carte Géol. France, 1916, p. 245; Mansfield, G. R., Physical and chemical character of New Jersey greensand, Econ. Geol., vol. 15, 1920, p. 567.
[652] Schneider, H., op. cit., 1927, p. 302.
[653] Cayeux, L., Contribution à l'étude micrographique des terrains sédimentaires, Mém. Soc. Géol. Nord, pt. ii, no. 2, 1897, pp. 176–184.

feral shells and that similar occurrences are in the Vicksburg of Mississippi and the Eocene of the Paris Basin.[654] Prather[655] and Mansfield,[656] on the contrary, note the difficulty of relating the glauconite of the New Jersey greensands to the shells of foraminifera and the latter states that it seems difficult to ascribe the formation of all glauconite to the agency of organic matter. Furthermore, the occurrence of glauconite in shells proves no causal relation. Collet[657] appears to have appealed to shell fillings very largely for an agent to place the clay in the form of pellets, the shell itself playing no direct part in the formation of glauconite; but if pellets of clay are essential as the first step in the formation of glauconite, it is not necessary to appeal to shells, as the abundant coprolitic material would serve to the same end. Many years ago Buchanan[658] emphasized the importance of coprolitic matter in the constitution of the bottom materials of the sea, the bottom muds in some cases seeming to be almost entirely composed of such, and he stated that he had been "able to trace a transition of the more earthy shore coprolites to the more mineralized and glauconitic pelagic ones." Quite recently similar relationship between coprolites and glauconite has been pointed out. In Japanese waters, in one case, the waters being fresh but closely connected with the sea, Takahashi and Yagi[659] have collected coprolitic pellets showing all transitions from those without a trace of glauconite to those completely glauconitized. The waters in which the glauconite particles and coprolites were collected were protected by shore topography and had maximum depths of 27 fathoms, the shallowest depth of collection being 1 fathom. The pellets from the fresh waters were collected in Kasumiga-Ura Lake, a body of water closely connected with the sea. These pellets seemed to be little glauconized.

Cayeux[660] has observed that arable soils contain particles showing a range from fresh glauconite to complete alteration into limonite, this suggesting that organic matter may play no part in glauconite formation and that it

[654] Dryden, A. L., jr., Glauconite in fossil foraminiferal shells, Science, vol. 74, 1931, p. 17.

[655] Prather, J. K., Glauconite, Jour. Geol., vol. 13, 1905, pp. 509–510.

[656] Mansfield, G. R., The physical and chemical character of the New Jersey greensand, Econ. Geol., vol. 15, 1920, pp. 563–565. See also, Potash in the greensands of New Jersey, Bull. 727, U. S. Geol. Surv., 1922, p. 139.

[657] Collet, L. W., op. cit., p. 132.

[658] Buchanan, J. Y., On the occurrence of sulphur in marine muds and nodules, and its bearing on their mode of formation, Proc. Roy. Soc. Edinburgh, vol. 18, 1890–91, pp. 17–39 (20–21).

[659] Takahashi, J., and Yagi, T., The peculiar mud-grains in the recent littoral and estuarine deposits, with special reference of the origin of glauconite. Ann. Rept. Saito Ho-on Kai, no. 5, 1929, pp. 44–59, Also Econ. Geol., vol. 24, 1929, pp. 838–852.

[660] Cayeux, L., Contribution à l'étude micrographique des terrains sédimentaires, Mém. Soc. Géol. Nord, pt. ii, no. 2, 1897, p. 165.

originates in surficial deposits under surface ground-water conditions. The writer has made the same observation, but the glauconite particles and those in process of alteration to limonite were derived from a glauconite-containing formation whose decay was responsible for the soil. Rather extensive observations do not favor the hypothesis that glauconite can form under surface conditions in the presence of an abundance of oxygen. Cayeux considers that finely divided glauconite may play an important rôle in the history of the larger glauconite particles, and postulates a continued growth of the particles in the deposits during and after consolidation. The large grains of glauconite above stratigraphic breaks, noted by Goldman, may thus be due to such growth, as would be favored by the generally high porosity and permeability of initial deposits. However, while such continued growth may be possible, there seem to be few, if any, supporting facts.

The existing state of knowledge with respect to the origin of glauconite supports the view that it is a product of diagenesis and that the glauconitic particles were originally pellets of mud containing finely divided and colloidal clay and iron oxide; that in some as yet unknown manner the aluminum of the clay was removed and its place taken by colloidal iron, and potash and colloidal silica were absorbed from the sea water or surrounding materials. The botryoidal shapes of the particles suggest additions of glauconite thereto from the surrounding waters, but nothing is known as to direct precipitation of glauconite from materials in solution. The alteration of the mud pellets to glauconite may take place on the surface of the sea bottom or in the sediments beneath the bottom surface. An environment intermediate between strongly reducing and strongly oxidizing seems necessary. The preparation of the colloidal ferric hydroxide and the potash may in part be due to decaying organic matter acting upon iron- and potassium-bearing clay and silicates. No glauconite is known to have been formed in fresh waters, except the one doubtful case in Japan in which it is possible that the particles were transported after their formation. The formation of glauconite in soils has yet to be proved. While celadonite is an alteration product of augite and has been stated to be like glauconite, there are sufficient differences in the chemical compositions of the two to warrant the view that they are distinct substances.

Gypsum, Rock Salt, and Other Saline Residues

General Considerations

The most important saline residues are rock salt, gypsum, and anhydrite. There are many others of importance, but few of them form rock masses.

The chief process involved in the formation of these substances is the evaporation of water in which the constituent materials are contained in solution, although some, as gypsum, may be precipitated by chemical reactions without evaporation, and a few have resulted from the freezing of water. Some are formed through replacement of other substances, gypsum replacing limestone probably being the most common example, and some are developed through metamorphism of saline residues due to original precipitation.

The various substances may be divided into chlorides, sulphates, carbonates, nitrates, and borates. The important chlorides are rock salt ($NaCl$), sylvite (KCl), douglasite ($K_2FeCl_4 \cdot 2H_2O$), carnallite ($KMgCl_3 \cdot 6H_2O$), tachyhydrite ($2MgCl_2 \cdot CaCl_2 \cdot 12H_2O$), and bischofite ($MgCl_2 \cdot 6H_2O$). The sulphates are many. Those occurring in the Stassfurt region are anhydrite ($CaSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$), glauberite ($CaSO_4 \cdot Na_2SO_4$), polyhalite ($CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$), krugite ($K_2SO_4 \cdot 4CaSO_4 \cdot MgSO_4 \cdot 2H_2O$), kieserite ($MgSO_4 \cdot H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), vanthoffite ($MgSO_4 \cdot 3Na_2SO_4$), bloedite (astrakanite) ($MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$), loewite ($MgSO_4 \cdot Na_2SO_4 \cdot 2\frac{1}{2}H_2O$), langbeinite ($2MgSO_4 \cdot K_2SO_4$), leonite ($MgSO_4 \cdot K_2SO_4 \cdot 4H_2O$), picromerite ($MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$), aphthitalite ($K_3Na(SO_4)_3$), and kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$). Celestite is also present. Other sulphates which are formed in the bitter lakes are thenardite (Na_2SO_4), hanksite ($9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$), and others of rare occurrence. The carbonates are calcite, aragonite, dolomite, thermonatrite ($Na_2CO_3 \cdot H_2O$), natron ($Na_2CO_3 \cdot 10H_2O$), trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$), and gaylussite ($CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$). The nitrates are those of sodium and potassium. The borates are borax ($Na_2B_4O_7 \cdot 10H_2O$), colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$), searlesite ($Na_2O \cdot B_2O_3 \cdot 4SiO_2 \cdot 2H_2O$), ulexite ($NaCaB_5O_9 \cdot 8H_2O$), and kernite[661] ($Na_2B_4O_7 \cdot 4H_2O$).

If pure, these various salts are transparent to white and gray in color. Not uncommonly, however, they contain other substances, as clay, iron oxide, organic matter, and then the colors become blue, red, and even black. Amorphous or microcrystalline gypsum and anhydrite are known as rock gypsum or alabaster, and this is the variety commonly occurring in thick beds. The macrocrystalline variety of gypsum, selenite, ordinarily occurs as individual crystals in clays and as veins and bands in the clay beds associated with the rock gypsum. Crystals of selenite are also not uncommon in clayey strata containing some carbonaceous matter. Satin spar, a variety with fibrous structure, is commonly found in veins. Gypsite is an earthy form of gypsum.

In so far as these substances are the result of evaporation, they develop

[661] Schaller, W. T., Science, vol. 67, 1928, p. x.

through evaporation of sea water, the waters of lakes and playas, or waters brought to the surface by springs or capillary action.

The average salinity of sea water is 35 permille or 35 grams of salts per liter of normal sea water. This is about 3.5 per cent of the water by weight. The salinity differs slightly in the different oceans, and there are decided differences in different parts of the same ocean, it being lowest in those parts receiving a large influx of fresh water and highest in confined bodies adjacent to dry lands. Krümmel shows for each ocean a low content in a belt adjacent to the equator, a rise toward each of the two Tropics, and a fall toward the polar regions.[662] The content is high in such waters as the Red Sea and such enclosed basins as the Dead Sea and Great Salt Lake, being in the former 992.15 permille at the surface and 259.98 permille at 300 meters depth, and in the latter ranging from 137.90 permille to 277.20 permille.[663]

The elements in sea water in percentages and parts per million are given in table 60.[664] Table 61 gives the content estimated as salts in percentages of total solids.[665] This table shows that sodium and magnesium chlorides constitute the major portion of the salts in solution. The following elements have been detected: Aluminum, barium, boron, cæsium, cobalt, copper, iron, lead, lithium, manganese, nickel, radium, rubidium, strontium, and zinc. Moberg states that the elements given in the second part "of the table bear a constant ratio to each other and the total salt" and Bigelow[666] is in accord in his statement that "Whether the sample be taken in the Atlantic, in the Pacific, or in the Indian Ocean, in high latitudes or in low, the total solutes are found to be about 54 per cent chlorine; about 31 per cent sodium; about 4 per cent magnesium, about 1 per cent potassium; 1 per cent calcium; and about 0.2 per cent bromine, with about 8 per cent of sulphate radicals, about 0.2 per cent of carbonate radicals." While it is not certain that the ratios of these elements have always been as they are at present, their present distribution in all seas in approximately the same ratios is strongly suggestive that such may always have been the case. It is not improbable that the total solid content of the sea has experienced considerable variation throughout geologic time.

The evaporation of sea or other salt waters precipitates the substances in solution in reverse order to solubility and extent of saturation, with various modifications arising from interactions of the various substances in

[662] Krümmel, O., Handbuch der Ozeanographie, 1907, p. 334.
[663] Clarke, F. W., Data of geochemistry, 1924, pp. 157, 171.
[664] Moberg, E. G., Letter of August 25, 1931.
[665] Grabau, A. W., Geology of the non-metallic mineral deposits, vol. 1, Principles of salt deposition, 1920, p. 51.
[666] Bigelow, H. W., Oceanography, 1931, p. 110.

TABLE 60

ELEMENT	PER CENT		PART PER MILLION
O	85.8	96.5	858,000
H	10.7		107,000
Cl	1.94	3.4	19,400
Na	1.14		11,400
Mg	0.14		1,400
S	0.09		900
Ca	0.04		400
K	0.04		400
Br	0.007		70
C	0.003		30
F	0.00008		0.8
Si	0.00002		0.2
N	0.00002		0.2
I	0.000005		0.05
As	0.000001		0.01
P	0.000002		0.02
Ag	0.000001		0.01
Au			0.000,005

TABLE 61

SALT	PER CENT OF TOTAL SOLIDS	GRAMS PER LITER
$NaCl$	77.758	27.213
$MgCl_2$	10.878	3.807
$MgSO_4$	4.737	1.658
$CaSO_4$	3.600	1.260
K_2SO_4	2.465	0.863
$CaCO_3$*	0.345	0.123
$MgBr_2$	0.217	0.076
	100.000	

* Includes all traces of other salts.

solution to temperature, sunlight, and probably other factors. The problem has been investigated by Usiglio,[667] who evaporated sea water obtained in

[667] Usiglio, J., Analyse de l'eau de la Méditerranée sur les Côtes de France, Annales des Chim. et Phys., vol. 27, 1849, pp. 92–107; Études sur la composition de l'eau de la Méditerranée sur l'exploitation des sels qu'elle contient, Ibid., 1849, pp. 172–191; see also Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 220.

the Mediterranean off Cette on the south coast of France, the water having an initial salinity of 38.45 permille. Preliminary analyses showed that the composition of the water with possible combinations was as given in table 62.

This experiment was conducted in duplicate, 5 liters of sea water being used in each case, one sample having been obtained 3000 meters from shore and about 1 meter beneath the surface, the other 5000 meters from shore and at the same depth. Each sample was evaporated in a large porcelain dish kept in a hot house with temperature maintained at 40°C., the air being kept dry by use of quicklime. From time to time the liquids were removed from the hot house, cooled to ordinary temperature of 21°C., the liquids decanted, and the precipitates filtered, dried, and weighed. The order of precipitation and quantities of the different precipitates are given in table 63, the weights being in grams per liter.

Evaporation of the last bitterns gave interesting and variable results: The fall of temperature from that of day to that of night precipitated additional magnesium sulphate, which with warming of the water to day temperatures partially redissolved. Further evaporation precipitated sodium chloride and magnesium sulphate; cooling led to precipitation of more magnesium sulphate; and still further evaporation formed a deposit of magnesium sulphate, the double sulphate of magnesium and potassium, sodium chloride, and magnesium chloride and bromide. Continued evaporation and decantation led in succession to the deposition of the double chloride of potassium and magnesium with which at times was associated the double sulphate of potassium and magnesium. The final precipitate was magnesium chloride ($MgCl_2 \cdot 6H_2O$). This gave an order of deposition of salts from the mother liquor as follows:

1. Night—epsomite—$MgSO_4 \cdot 7H_2O$
2. Day—hexahydrate—$MgSO_4 \cdot 6H_2O$; halite—NaCl; and rarely potash salts
3. Night—epsomite—$MgSO_4 \cdot 7H_2O$
4. Day—hexahydrate—$MgSO_4 \cdot 6H_2O$; schönite—$MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$; halite—NaCl; bischofite—$MgCl_2 \cdot 6H_2O$; magnesium bromide—$MgBr_2$
5. Afternoon—carnallite—$MgCl_2 \cdot KCl \cdot 6H_2O$
6. Night—carnallite, schönite
7. Day—little deposition
8. Afternoon—carnallite
9. Night—carnallite, epsomite
10. Autumn, some months later, temperature 5° to 6°C., bischofite.

The results obtained by Usiglio show that evaporation of sea water produces precipitates, or evaporites,[668] in the following order: calcium carbonate and iron oxide, calcium sulphate with its precipitation overlapping that

[668] Berkey, C. P., The new petrology, Bull. 251, N. Y. State Mus., 1929, pp. 105–118.

TABLE 62

SALT	GRAMS IN 100 GRAMS SEA WATER	GRAMS PER LITER
Fe_2O_3	0.0003	0.003
$CaCO_3$	0.0114	0.117
$CaSO_4$	0.1357	1.392
$MgSO_4$	0.2477	2.541
$MgCl_2$	0.3219	3.302
KCl	0.0505	0.518
NaBr	0.0556	0.570
NaCl	2.9424	30.183
Water	96.2345	987.175
Totals	100.0000	1025.801
$CaSO_4 \cdot 2H_2O$	0.1716	1.76
$MgSO_4 \cdot 7H_2O$	0.5051	5.181

TABLE 63

VOLUME	Fe_2O_3	$CaCO_3$	$CaSO_4 \cdot 2H_2O$	NaCl	$MgSO_4$	$MgCl_2$	NaBr	KCl
1.000								
0.533	0.0030	0.0642						
0.316		Trace						
0.245		Trace						
0.190		0.0530	0.5600					
0.1445			0.5620					
0.131			0.1840					
0.112			0.1600					
0.095			0.0508	3.2614	0.0040	0.0078		
0.064			0.1476	9.6500	0.0130	0.0356		
0.039			0.0700	7.8960	0.0262	0.0434	0.0728	
0.0302			0.0144	2.6240	0.0174	0.0150	0.0358	
0.023				2.2720	0.0254	0.0240	0.0518	
0.0162				1.4040	0.5382	0.0274	0.0620	
Total	0.0030	0.1172	1.7488	27.1074	0.6242	0.1532	0.2224	
Salts in last bittern				2.5885	18.545	3.1640	0.3300	0.5339
Total solids	0.0030	0.1172	1.7488	29.6959	2.4787	3.3172	0.5524	0.5339

of calcium carbonate, sodium chloride with precipitation beginning before completion of that of calcium sulphate and continuing to association with precipitates of other sulphates, chlorides, and bromides.

This theoretical succession of salt deposits does not always obtain. In many cases gypsum or anhydrite does not have underlying strata of calcium carbonate. There are also occurrences of rock salt without the calcium sulphate, although the latter usually occurs somewhere in the region in the same formation. Salts other than calcium carbonate, calcium sulphate, and sodium chloride are not commonly present in significant quantities.

Naturally these experiments did not extend over periods of time comparable to those responsible for natural deposits and hence did not imitate nature in that respect. It seems certain that the formation of the important deposits of saline residues required long periods of time, that extensive changes of temperature took place during their deposition, that there probably were considerable fluctuations in salinity due to occasional influx of fresh water, and that the deposits ultimately were subjected to high pressures and rise of temperature, consequent upon burial. Usiglio did not obtain kieserite, polyhalite, kainite, and anhydrite, the last possibly because the temperature maintained was not sufficiently high.

It should be noted that the order of precipitation shown in Usiglio's experiments does not permit the formation of pure sodium chloride, and that pure calcium sulphate forms over a very narrow range. According to Stieglitz[669] and Wilder,[670] all calcium sulphate deposits formed by evaporation of waters of seas and stream-fed lakes under existing atmospheric conditions with respect to carbon dioxide content must contain 0.9 per cent of calcium carbonate. Carbon dioxide probably has been in the atmosphere from the latter's beginning, but it seems quite certain that large fluctuations have existed. It is also probable that the quantities of lime and also of other salts in solution in the ocean have been subject to variations. The two factors may permit calcium sulphate deposits with an entirely different calcium carbonate content.

As a general proposition, it is probable that incomplete rather than complete evaporation of a salt-water body has been the rule, and that a concentration has not often been attained to bring about precipitation of the mother-liquor salts, or even of the sodium chloride, and that calcium sulphate is commonly the end product of evaporation. There seems to be a greater number of calcium sulphate deposits than of sodium chloride. Also, after deposition the salts of latest precipitation are so soluble that their subsequent re-solution is likely unless a covering of impervious material, as clay, compels their preservation. It is probable that large bodies very

[669] Stieglitz, J., The tidal and other problems, Publ. 107, Carnegie Inst. of Washington, 1909.

[670] Wilder, F. A., Some conclusions in regard to the origin of gypsum, Bull. Geol. Soc. Am., vol. 33, 1922, pp. 386–394.

rarely reached the mother-liquor stage of concentration. In small bodies the opportunities for the dissipation of the mother-liquor salts are so great that the chances of preservation are small.

Calcium sulphate exists in nature in the two forms of gypsum and anhydrite. It is not certain, however, that present forms are those of the times of deposition. Under surface conditions in pure water, anhydrite slowly changes into gypsum at almost any temperature.[671] Such is known to have occurred in the deposits of New York, Ontario, Nova Scotia, Kansas, and many other localities. On the other hand, if gypsum is buried sufficiently deeply, both the increase in pressure and the increase in temperature favor its dehydration and change to anhydrite. Van't Hoff and Weigert[672] found that when solutions of calcium sulphate are evaporated in open containers under atmospheric pressure, gypsum or anhydrite is deposited depending upon the temperature reached at saturation. Below 66°C. the precipitate is gypsum, above that temperature anhydrite. The presence of other salts in the solution lowers the boundary temperature for gypsum-anhydrite deposition, and if the other salt is sodium chloride, the critical temperature is 30°C.; and Vater[673] concludes that only with temperatures above this boundary can calcium sulphate separate as anhydrite. For concentrated solutions of sodium chloride Van't Hoff and Weigert found that anhydrite begins to form at 25°C.[674] and thus "from the beginning of rock salt deposition only anhydrite is to be reckoned with." Variations in temperature would give rise to alternations of gypsum and anhydrite.

As most saline residues seem to have originated under arid conditions, it seems probable that anhydrite was formed in hot desert regions with tropical and subtropical climates, and that the deposition of gypsum took place in the cooler deserts of temperate regions.

Van't Hoff and his associates studied the formation of salts occurring in saline residues as single substances in solution, their interactions when two or more were in solution, and the effects of temperature and other factors. At 20°C., 100 g. of water will dissolve 26.4 g. of NaCl or 25.6 g. KCl; at 50°C., 26.8 g. NaCl, or 30 g. KCl, showing very different increases in solubility with rise in temperature. If the two salts are placed in solution, 100 g. of

[671] Goldman, M. I., Petrography of salt dome cap rock, Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, p. 77.

[672] Van't Hoff, J. H., and Weigert, F., Untersuchungen über die Bildungsverhältnisse der oceanischen Salzablagerungen, insbesondere des Stassfurter Salzlagers, Sitzb. k. Preuss. Akad. d. Wiss., vol. 23, 1901, pp. 1140–1148.

[673] Vater, H., Einige Versuche über die Bildung des marinen Anhydrites, Sitzb. k. Preuss. Akad. d. Wiss., 1900, pp. 265–295.

[674] Van't Hoff, J. H., and Weigert, F., op. cit.; Grabau, A. W., Principles of salt deposition, 1920, pp. 61–67, 178.

water at 20°C. will dissolve 20.3 g. NaCl and 10.2 g. KCl, but at 50°C. only 18.5 g. NaCl and an increase in KCl to 14.7 g. It is obvious that evaporation with rise of temperature would precipitate NaCl. This is an application of the Nernst law that the solubility of a salt decreases with the presence in the solution of a second salt with a common ion.[675] If a salt with no common ions is introduced into the solution, the solubility is increased in accordance with the Noyes generalization.[676] It is obvious also that in a solution so complex as sea water there would be different degrees of solubility as temperatures changed and different substances were precipitated. Each of the three cations, Na, K, and Mg, and also the Ca, can unite with each of the two anions of Cl and SO_4, so that many combinations are possible, and the single compounds might unite with each other to form

TABLE 64

DOUBLE SALTS	COMPOSITION	MOLS. IN 1000 MOLS. H_2O.						TEMPERATURE
		NaCl	KCl	$MgCl_2$	Na_2SO_4	K_2SO_4	$MgSO_4$	°C.
Carnallite	$MgCl_2 \cdot KCl \cdot 6H_2O$		6	89				25
Schönite	$MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$					11	40	25
Glaserite	$3K_2SO_4 \cdot Na_2SO_4$	88	30		9			25
Kainite	$MgSO_4 \cdot KCl \cdot 3H_2O$	11	12	61			12	25
Leonite	$2MgSO_4 \cdot K_2SO_4 \cdot 4H_2O$	24	20	40			17	25
Astrakanite	$Na_2SO_4 \cdot MgSO_4 \cdot 4H_2O$	75		2			27	25
Langbeinite	$2MgSO_4 \cdot K_2SO_4$	43	42	36			11	83
Loewite	$2MgSO_4 \cdot 2Na_2SO_4 \cdot 5H_2O$	53		34			12	83
Vanthoffite	$MgSO_4 \cdot 3Na_2SO_4$	86		13			12	83

double salts, and as water is present each of these might unite with water to form hydrates. This last might be prevented in the presence of such dehydrating materials as $CaCl_2$ or $MgCl_2$.

Table 64 lists the double salts, occurring in the Stassfurt deposits, which have been shown by Van't Hoff and his associates to be capable of formation at the temperatures and from the solutions shown.

The temperature of 83°C. or 181.4°F. is too high to have extensive prevalence in surface waters, and extensive occurrence of langbeinite, loewite, and vanthoffite probably should be referred to changes subsequent to deposition.

With waters at 25°C., with composition in molecules per thousand mole-

[675] Nernst, W., Theoretische Chemie, 1926, p. 613.
[676] Noyes, A. A., Zeits. phys. Chem., Bd. 6, 1890, p. 241, and subsequent papers.

cules of water of 24 NaCl, 15.5 KCl, 40.7 $MgCl_2$, and 20 $MgSO_4$, the condition of saturation for these salts, the above students found the following listed salts and sodium chloride to separate on evaporation in the order listed.

1. Magnesium sulphate
2. Magnesium sulphate and kainite
3. Hexahydrate and kainite
4. Kieserite and kainite
5. Kieserite and carnallite
6. Kieserite, carnallite, and magnesium chloride

From sea waters of normal proportion at 25°C., containing in molecules 100 NaCl, 2.2 KCl, 7.8 $MgCl_2$, and 3.8 $MgSO_4$ to 1000 molecules H_2O, the salts of table 65 separated in the order and quantities shown. This is saturated for NaCl, but not for the other salts.

TABLE 65

	ROCK SALT	KIESERITE	KAINITE	CARNALLITE	BISCHOFITE
1	95.40				
2	4.42	1.05	2.02		
3	0.03	0.35		0.10	
4	0.15	0.38		0.08	7.62
Totals......	100.00	1.78	2.02	0.18	7.62

The relations of K_2 to Mg, and SO_4 to Mg, in salt deposits are different from what they are theoretically in sea water, as shown in the following figures:[677]

	K_2:Mg	SO_4:Mg
Sea water theoretically..............................	1:10.9	1:3
Salt deposits..	1:4.33	1:1.57

A comparison of the relative proportions in terms of thickness of deposits of the different common salts possible in sea water compared to the same salts in the Stassfurt deposits is given in table 66.[678] The rock salt is taken as 100 meters. This table shows an increase in anhydrite above that which may be expected from direct evaporation of sea water, but decreases in magnesium and potash, both forming salts that are quite soluble and hence readily removed.

[677] D'Ans, J., Untersuchungen über die Salzsysteme ozeanischer Salzablagerungen, Kali, 1915, p. 268.

[678] Erdmann, E., Die Entstehung der Kalisalzlagerstätten, Zeits. Angew. Chemie, vol. 21, 1908, pp. 1685–1702.

The complete evaporation of the waters of an arm of the ocean or a salt lake would not produce a great thickness of salt over the entire area of deposition. At the base would be a thin band of calcium carbonate containing iron oxide; this would be succeeded upward by calcium sulphate, either in the form of gypsum or anhydrite; and the calcium sulphate would be overlain by rock salt succeeded by the salts of the last bitterns. The calcium sulphate would merge at the base with calcium carbonate and at the top with sodium chloride, and the latter toward the top would be associated with, and gradually pass into the salts of the last bitterns. After a sea water has evaporated to the extent of precipitating most of the calcium sulphate, some of the remainder of the latter may unite with sodium sulphate to form glauberite, as is now occurring in the Gulf of Kara Boghaz, and as this concentration increases, langbeinite may form. These two salts are

TABLE 66

	SEA WATER—THICKNESS OF KINDS OF SALTS FORMED FROM PRECIPITATES	STASSFURT DEPOSITS—THICKNESS OF KINDS OF SALTS PRESENT
	meters	*meters**
Anhydrite	3.4	5.7
Rock salt	100.0	100.0
Kieserite	7.2	2.2
Carnallite	14.0	4.7
Bischofite	23.5	

* If the anhydrite beneath the rock and other salt beds is considered, this figure becomes 20.4.

both present in primary form in the anhydrite region of the older rock salt of the Stassfurt district. Each 1000 feet of average sea water would make a deposit about 15 feet thick, of which only 0.7 foot would be gypsum. To form a bed of gypsum with thickness of 10 feet would require the evaporation of sea water equivalent to a depth of around 14,000 feet. It may be considered impossible that a water body with depth of 14,000 feet ever reached the degree of concentration necessary to deposit calcium sulphate. But thicknesses of calcium sulphate of many hundreds of feet are known, hence it is obvious that their origin cannot be due to simple evaporation of an enclosed body of water, and exceptional conditions for their formation must have existed. Likewise, salt beds of such immense thickness exist that direct evaporation of a water body cannot be responsible for their origin.

Among the thick gypsum or anhydrite deposits of North America are the following: At Hillsborough, Nova Scotia, there is a formation of essentially

pure gypsum and anhydrite with thickness of around 250 feet.[679] The calcium sulphate beds of New York range in thickness to about 75 feet and have been stated to lie entirely above the salt beds of the same region. This is very questionable in many instances and is certainly not true in some.[680] It was Dana's[681] opinion that the calcium sulphates of the Salina resulted from the alteration of limestone. This probably was the case for some, but there seem to be few facts supporting this hypothesis of origin for most of the New York calcium sulphate deposits. The salt and gypsum beds range through a thickness of 1000 to 1500 feet, with maximum thickness of rock salt exceeding 300 feet and with beds of pure or nearly pure rock salt ranging in thickness up to around 75 feet, and in a well at Watkins a bed of rock salt 265 feet thick has been recorded. The maximum thickness in Kansas of individual beds of calcium sulphate is about 60 feet; a somewhat greater thickness is given for Oklahoma.[682] Udden[683] has described a well core from western Texas which contains calcium sulphate through 1950 feet, of which 1164 feet represent an essentially continuous deposit of anhydrite. The entire calcium sulphate portion of the core is laminated, with the units averaging less than 2 mm. in thickness. These laminations may have seasonal significance, and this hypothesis has been suggested for similar lamination in other salt deposits. The rock-salt beds of the Permian basin of western Texas also have great thickness.

In general, the thickness of rock salt in the regions of its occurrence exceeds the thickness of the calcium sulphate in the same region. In some cases the latter may have a greater thickness than given in well logs, because of its being identified by drillers as limestone. Beds of carbonate may lie immediately or not far below those of calcium sulphate, but in many instances the underlying beds are shale and less often sandstone.

The salt beds of the geologic column are usually without fossils, and such is very commonly, but not always, the case in the associated strata. Organic matter has been found in salt beds, and in a few instances fossils seem to be

[679] Kramm, H. E., The Hillsborough gypsum district, Guide Book, no. 1, pt. ii, 13th Intern. Geol. Cong., Geol. Surv. Canada, 1913, p. 362.

[680] Hartnagel, C. A., Culmination and decline of the Salina sea, in Bull. 69, New York State Mus., 1903, pp. 1158, 1160; Alling, H. L., The geology and origin of the Silurian salt of New York State, Bull. 275, New York State Mus., 1928; Newland, D. H., Recent progress in the study of the Salina formation, Rept. Comm. on Sedimentation, Nat. Research Council, 1927–1928, pp. 36–43; Idem., The gypsum resources and gypsum industry of New York, Bull. 283, New York State Mus., 1929.

[681] Dana, J. D., Manual of geology, 4th ed., 1925, p. 554.

[682] Snider, L. C., The gypsum and salt of Oklahoma, Bull. 11, Oklahoma Geol. Surv., 1913, p. 28.

[683] Udden, J. A., Laminated anhydrite in Texas, Bull. Geol. Soc. Am., vol. 35, 1924, pp. 347–354.

abundant. The upper Eocene of the Paris Basin contains a 65-foot gypsum member which is said to contain bones of mammals, shells, and wood.[684]

TABLE 67

ANALYSES OF ROCK SALT

	1	2
NaCl	97.51	82.71
$MgCl_2$	0.10	
Na_2SO_4	0.57	5.32
K_2SO_4		8.43
$CaSO_4$	1.51	
Na_2CO_3		2.46
Fe_2O_3	0.11	0.15
Insoluble	0.20	
H_2O		0.82
	100.00	99.89

1. Salt from Kingman, Kansas.
2. Salt from bed in Katwee Lake, north of Albert Edward Nyanza region in Central Africa.

TABLE 68

ANALYSES OF GYPSUM

	1	2
SO_3	46.18	46.18
Cl	Trace	0.03
Al_2O_3, Fe_2O_3	0.10	0.08
CaO	32.37	32.33
MgO	Trace	0.05
Na_2O		0.14
K_2O	0.10	
H_2O	20.94	20.96
Insoluble	0.10	0.05
	99.79	99.82

1. Gypsum from Hillsborough, Nova Scotia.
2. Gypsum from Alabaster, Michigan.

Under the bar theory of origin of salt deposits (p. 496 *et seq.*) an abundance of fossils is to be expected. The fact that such is not commonly the case

[684] Snider, L. C., op. cit., p. 28.

suggests origin under conditions different from those postulated in that theory.

Tables 67 to 69 give analyses of rock salt, gypsum, and bittern from several localities.[685]

Important deposits of saline residues are those of Stassfurt, and the deposits of the Salina formation of New York and adjacent states; the gypsum, anhydrite, and salt deposits of the Permian of Kansas, Oklahoma, and Texas and the Permian and Triassic of the Great Plains country in general; the various salt deposits of the playas and extinct and shrinking lakes of California, Nevada, and other western states; the nitrate deposits of western South America; etc. These are considered in greater or less detail in succeeding paragraphs.

TABLE 69

ANALYSES OF BITTERN

	1	2
Cl	56.33	63.93
Br	0.94	1.16
I		Trace
SO_4	9.28	0.06
Na	22.23	10.24
K	2.58	5.27
Ca	0.38	11.26
Mg	7.56	8.08
	99.30	100.00
Salinity permille	318.20	325.67

1. Bittern from Leslie Salt Refining Work, San Mateo, Calif.
2. Bittern from maximum concentration, Syracuse, N. Y.

The section given below shows the succession of strata in a portion of the salt beds of the Salina basin of Kansas. There is great variation in thickness of the individual salt beds, but they are known to have a maximum thickness of about 275 feet. The section, which is typical, shows that shales and limestones are the common rocks separating the salt beds of this basin and that sandstone is rare.

[685] Clarke, F. W., op. cit., pp. 231–233.

Record of well at Lyons, Kansas[686]

	Feet
Soil and sandy loam	45
Sandstone	10
Clays and shale	55
Sandstones	88
Red sandy shale	56
Red clay	18
Soft limestone	3
Gypsum and limestone	9
Blue shale	4
Red and blue shale mixed with gypsum	292
Dark gray and reddish gray shales	213
Rock salt, reddish at bottom	13
Gray shale	8
Rock salt	10.5
Gray shale and salt mixed	3
Gray shale	4
Rock salt	9
Rock salt and shale	1.5
Rock salt	8.5
Gray shale	1.5
Rock salt	8.5
Shale	1
Rock salt	6.5
Rock salt and shale	11
Rock salt, crystal	4
Rock salt and shale	25.5
Dark red shale	6
Rock salt and rock	10
Rock salt	17
Rock, and salt and shale	40
Rock salt	2
Shale	1
Rock salt	9.5
Shale	0.5
Rock and salt and a little shale	10

The Permian basin of western Texas, the Michigan basin, and the Salina basin of New York would yield somewhat similar sections. A section from the Permian basin of western Texas would show a much greater development of calcium sulphate in some localities, a great development of limestone or dolomites in others, and some sections would show a great thickness of salt beds.

Probably the most extensively studied salt deposits are those of the Stassfurt region, and these likewise possess the most extensive known occurrences

[686] Haworth, E., Mineral resources of Kansas, 1896, Article on salt.

of the mother-liquor salts. The descending section of the Stassfurt region is as follows:[687]

10. Surface materials, variable thickness.
9. Shales, sandstones, and clays, variable thickness.
8. Younger rock salt, variable thickness, missing in places.
7. Anhydrite, usually present, 30 to 80 meters.
6. Salt clay, occasionally absent, average thickness 5 to 10 meters.
5. Carnallite zone, 15 to 40 meters thick. At one place a bed of rock salt lies between 5 and 6, and in parts of the region kainite overlies the carnallite, is in turn overlain by "sylvenite" or hartsalz, and that in turn by schönite.
4. Kieserite zone.
3. Polyhalite.
2. Older rock salt and anhydrite. The anhydrite is in layers whose average thickness is about 7 mm.; these layers separate salt units of 8 to 9 cm. thickness. These layers have been referred to seasonal deposition, but the validity of the interpretation is uncertain. Zones 2–4 have a thickness ranging from 150 to perhaps 1000 meters.
1. Anhydrite and gypsum.

A well drilled near Amsdorf gave the following descending section:[688]

	Meters
Sand and gravel	16.30
Clay and gravel	59.40
Red sandstone	88.00
Gypsum	48.30
Older rock salt	1076.90
Anhydrite	2.60
"Stinkstein"	3.50
"Stinkstein" with gypsum	7.00
Gypsum	1.30
Anhydrite with "Stinkstein"(*)	18.70
White, crystalline rock salt	15.00
Anhydrite	41.50
"Zechstein" and "Faule"	3.50
Kupferschiefer	0.54
Weisliegende*	0.46
	1383.00

* Stinkstein, Zechstein, Faule, and Weisliegende are German stratigraphic terms.

It was shown by Van't Hoff[689] and his associates that the evaporation of sea water would produce a sequence of salt deposits possible of arrangement

[687] Clarke, F. W., op. cit., p. 223.

[688] Arrhenius, S., and Lachmann, R., Die physikalisch-chemischen Bedingungen bei der Bildung der Salzlagerstätten und ihre Anwendung auf geologische Probleme, Geol. Rundschau, Bd. 3, 1912, p. 151.

[689] Van't Hoff, J. H., Zur Bildung der ozeanischen Ablagerungen, Bd. 2, 1909, p. 40.

into five zones, and several of these zones were further subdivided by Rinne.[690] The result is as follows:

Zones	*Van't Hoff*		*Rinne*	
E.	Rock salt with bischofite, carnallite, and kieserite	62 m.	Bischofite zone	Sodium chloride with bischofite, kieserite, and carnallite
D.	Rock salt with kieserite and carnallite	6 m.	Carnallite zone	Sodium chloride with kieserite and carnallite
C.	Rock salt with kieserite and kainite	24 m.	Kainite zone	Sodium chloride with kieserite, kainite, hexahydrate, kainite, reichardtite, kainite
B.	Rock salt with bloedite (astrakanite) or reichardtite	8 m.	K-containing	Sodium chloride with reichardtite, leonite
			K-free $MgSO_4$ zone	Sodium chloride with reichardtite, bloedite (astrakanite)
			Polyhalite zone	Sodium chloride with polyhalite
A.	Rock salt		Anhydrite zone	Sodium chloride with anhydrite
			Gypsum zone	Sodium chloride with gypsum Sodium chloride without gypsum

The succession in the Stassfurt deposits does not seem to be such as would arise from direct evaporation of sea water. Reference to the table on page 470 shows that there is considerably less magnesium chloride than evaporation of sea water would yield.[691] This, however, is readily explainable on the basis of the high solubility of this salt and its consequent easy removal. There is also too much anhydrite or gypsum. Likewise, the Stassfurt deposits are lacking in, or do not have in well developed form, zones B and E, and the sodium chloride in zone D is far greater than can

[690] Rinne, F., Die geothermischen Metamorphosen und die Dislokationen der deutschen Kalisalzlagerstätten, Fortschritte d. Min., etc., vol. 6, 1920, pp. 101–136 (p. 113).

[691] Erdmann, E., Die Entstehung der Kalisalzlagerstätten, Zeits. Angew. Chemie, vol. 21, 1908, pp. 1685–1702.

exist in a solution saturated in carnallite. Another difference is the presence in the Stassfurt deposit of salt minerals which are not formed on evaporation of sea water under temperature conditions normal to the earth's surface. According to Van't Hoff,[692] the salts listed below, all of which occur in the Stassfurt deposits, required for their formation temperatures as follows.

Glauberite, formed above 10°C. (40°F.)
Hexahydrate, formed above 13°C. (57.4°F.)
Thenardite, formed above 15.5°C. (61.9°F.)
Kieserite, formed above 18°C. (64.4°F.)
Langbeinite, formed above 37°C. (98.6°F.)
Loewite, formed above 43°C. (109.4°F.)
Vanthoffite, formed above 46°C. (114.8°F.)
Loewite with glaserite, formed above 57°C. (134.6°F.)
Loewite with vanthoffite, formed above 60°C. (140°F.)
Kieserite with sylvite, formed above 72°C. (161.6°F.)

It is improbable that several of these temperatures are likely in surface waters, although it is known that temperatures above 70°C. do occur in the deeper waters of some salt lakes.[693] Hence, it has been concluded that in many cases the salts are not in their original condition, but by reason of the pressure to which they have been subjected through burial beneath thick accumulations of sediments and crustal deformation, and of the increase in temperature consequent to burial and deformation, there has been recrystallization of the original minerals, resulting in the formation of new salts (designated metasalts by Grabau), so that the existing deposits may properly be said to have been metamorphosed.[694]

ENVIRONMENTAL CONDITIONS LEADING TO THE DEPOSITION OF SALINE RESIDUES

It is thought that the different varieties or types of saline residues result from the occurrence of the following conditions or environments: (1) deposition from springs through evaporation, freezing, or other changes; (2) deposition from ground water upon, or just beneath the surface; (3) mechanical deposition by wind and possibly by water; (4) evaporation of the

[692] Van't Hoff, J. H., Zeits. Electrochemie, vol. 2, 1905, p. 709.

[693] Grabau, A. W., Geology of non-metallic mineral deposits, vol. 1, Principles of salt deposition, 1920, p. 77.

[694] On this phase of salt deposits there should be consulted Rinne, F., Die geothermischen Metamorphosen und die Dislokationen der deutschen Kalisalzlagerstätten, Fortschritte d. Min. etc., vol. 6, 1920, pp. 101–136 (113); Arrhenius, S., and Lachmann, R., Die physikalisch-chemischen Bedingungen bei der Bildung der Salzlagerstätten, etc., Geol. Rundschau, Bd. 3, 1912, pp. 139–157; Lachmann, R., Ekzeme und Tektonic, Zentralbl. f. Min. etc., 1917, pp. 414–426, Jänecke, E., Die Entstehung der deutschen Kalisalzlager, 1915, pp. 66–97. Rinne gives an extensive bibliography, pp. 129–136.

waters of playas, lakes, and marginal or isolated parts of the ocean or large lakes; (5) replacement of other substances.

Deposits of Springs

The various constituents of saline residues are present in greater or less abundance in most rocks. Circulating waters acquire these to some degree and ultimately may deposit them in rocks adjacent to, or upon, the surface, the different substances forming combinations permitted by the conditions. The most common substance seems to be calcium carbonate, already described, but any of the saline residue salts listed as primary may be deposited; most common are gypsum and rock salt, each possibly containing other rarer salts, the deposition ordinarily taking place about those points where the waters reach the surface as springs. The waters may be divided on the basis of maximum substances in solution into chloride, sulphate, carbonate, siliceous, nitrate, phosphate, borate, and acid waters, but there is every possible gradation among these different types.[695]

The gypsum deposited about springs is composed of small irregular crystals and plates and is known as gypsite or gypsum earth. The material is very soft and in some instances powdery. As connoted by the term earth, there is considerable incorporation of clay, sand, organic matter, etc. Deposits of gypsum of this origin are limited in extent and thickness, a few acres in area and 15 feet in thickness being probable maxima.[696]

Spring deposits of sodium chloride occur in Alberta and Manitoba, one described by Kindle having been formed about a spring which derives its waters from Silurian and Devonian limestones, the deposit covering an area 40 by 15 feet with an average thickness of about 10 inches. The interesting feature connected with this deposit is the fact that the precipitation of the salt is not a consequence of evaporation, but of the winter freezing.[697] McConnell,[698] Wallace,[699] and Rutherford[700] have described salt deposits of similar origin in the same general region.

Springs in the Mason Valley of the Lahontan Basin deposit sodium sulphate on the surface over which the waters flow. The waters are of

[695] For analyses see Clarke, F. W., op. cit., pp. 184–202.

[696] Stone, R. W., etc., Gypsum deposits of the United States, Bull. 697, U. S. Geol. Surv., 1920, p. 24.

[697] Kindle, E. M., Separation of salt from saline water and mud, Bull. Geol. Soc. Am., vol. 29, 1918, pp. 471–488.

[698] McConnell, R. G., Ann. Rept. Geol. Surv. Canada, vol. 5, 1893, p. 35 D.

[699] Wallace, R. C., The corrosive action of brine in Manitoba, Jour. Geol., vol. 25, 1917, pp. 459–466.

[700] Rutherford, R. L., Corrosion by saline waters, Trans. Roy. Soc. Canada, vol. 18, 1924, pp. 31–37.

low salinity and have temperatures ranging from about the mean for the region to 162°F. A section of such a deposit is as follows:[701]

Sodium sulphate with sodium chloride and some calcium carbonate, forms a hard white crust	1–2 inches
Soft mealy, or clayey sodium sulphate, calcium carbonate, calcium sulphate, etc.	2–7 inches
Clear, transparent crystals of sodium sulphate with some earthy impurities	6–8 feet
Saline clay	

Rather uncommon substances in spring deposits are the alums. Their deposition is local, and they are commonly derived either directly or indirectly from the oxidation of sulphides. They occur as incrustations and stalactites about springs, or other places where water issues from the ground. Alunite ($K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$) and alunogen ($Al_2(SO_4)_3 \cdot 18H_2O$) are the substances most commonly formed, the latter together with halotrichite ($FeSO_4 \cdot Al_2(SO_4)_3 \cdot 24H_2O$) occurring in large quantities in Granite County, New Mexico.[702]

Surface and Subsurface Efflorescences of Salts

Efflorescences are due to the evaporation of ground water brought near or to the surface by capillary action. This takes place in arid and semi-arid regions, giving rise to deposits known in the United States as alkali, caliche, tepetate, and some of the so-called hardpan, in India as reh, and in Egypt as sabach—substances of the same general character. The deposits may be either on the surface, or just beneath it. Irrigation without subsurface drainage hastens accumulation, so that in parts of Montana, Wyoming, and elsewhere, small areas have been abandoned, or have had their productivity impaired through accumulations of alkali which in places cover the ground like a white shroud. The deposits may reach a foot to several feet in thickness, or they may be in the form of isolated concretionary particles, as for instance an occurrence in central Kansas at depths up to about 4 feet beneath the surface which is known as the "kiel" bed.

Possibly the most common surface efflorescent salt is calcium carbonate which, as noted on earlier pages, may reach a thickness up to around a half-dozen feet. Usually parts contain considerable impurity, because of the original materials of the surface, and frequently the structure is pisolitic or concretionary.

[701] Russell, I. C., Geological history of Lake Lahontan, Mon. 11, U. S. Geol. Surv., 1885, p. 48.

[702] Hayes, C. W., The Gila River alum deposits, Bull. 315, U. S. Geol. Surv., 1917, pp. 215–223.

Artificially dried muds studied by Kindle[703] showed that sodium chloride was precipitated in the muds and on the surface in three different forms: an upper layer, a lower layer, and in mud cracks and disseminated through the dry mud. The upper layer was pure white and consisted of minute frost-like crystals. The lower was formed of acicular crystals in vertical position and held a small quantity of clayey matter in the lower part. The salt in the mud cracks and in the dry mud was in the form of cubical crystals with hopper-like faces.

The materials forming the alkali and caliche may be any of the salts to which reference has been made, the most common being calcium, sodium, and potassium sulphates, calcium and sodium carbonates, and calcium and sodium chlorides. They differ with locality, the differences being due to the nature of the rock and soil through which the water has passed on its way to the surface and to the origin of the water. In the analyses of table 70 they are grouped as sulphate-chloride salts and carbonate salts. The nitrate salts constitute an additional group.

The analyses give the chemical composition of the alkali and the arrangement into compounds, but state nothing respecting the varieties of minerals which may be formed therefrom. The presence of water during formation permits a wide range in variety.

Surface salt deposits dominantly composed of sodium carbonate are known as black alkalies; those mostly composed of sodium sulphate are white alkalies. There are all gradations between the two.

Nitrate deposits occur as surface and near-surface efflorescences and as those of caverns and similar relations. The latter generally have been considered derived from bat guano, but it has been shown by Hess[704] that the nitrogen might have been acquired from the soils and rocks above the caves. Hess' arguments have, however, been opposed by Nichols.[705] The complete history of the surface and near-surface deposits of nitrates has not yet been unraveled in a way to meet general acceptance.

Nitrogen compounds are known to form under some conditions of decay of organic matter. Concentrated excrements of birds, bats, and other animals are common sources, and rookeries of birds are well known for their accumulations of guano. These generally are rich in phosphates. Certain bacteria, as those infesting the roots of many Leguminosæ, have ability to fix atmospheric nitrogen. Some nitrogen compounds are also said to form in connection with volcanic activity and through discharges of atmospheric electricity.

[703] Kindle, E. M., op. cit., 1918.

[704] Hess, W. H., The origin of nitrates in cavern earths, Jour. Geol., vol. 8, 1900, pp. 129–134.

[705] Nichols, H. W., Nitrates in cave earths, Jour. Geol., vol. 9, 1901, pp. 236–243.

Nitrate deposits of the caliche type are mostly composed of sodium nitrate with potassium nitrate. One or more of the nitrates of barium, calcium, and magnesium and certain double salts containing nitrogen are usually associated. The most important occurrence of nitrates is in western South America.

TABLE 70

SULPHATE-CHLORIDE SALTS*

	A	B	C	D
NaCl	85.27	70.81	5.93	10.81
Na_2SO_4	1.75	26.38	94.04	53.14
Na_2CO_3	2.59			
K_2SO_4		1.94		32.34
$MgCl_2$				
$CaSO_4$				3.71
H_2O	8.57			
Isol. res.	1.82			
	100.00	99.13	99.97	100.00

CARBONATE SALTS

	E	F
Na_2CO_3	65.72	32.58
$NaHCO_3$		
Na_2SO_4		25.28
NaCl	3.98	14.75
$NaNO_3$		19.78
$Na_2B_4O_7$	8.42	2.25
K_2SO_4	20.23	3.95
$MgSO_4$	1.65	
KCl		
$(NH_4)CO_3$		1.41
SiO_2		
	100.00	100.00

* From Clarke, F. W., op. cit., pp. 237–238. A and B from Nevada, C from Arizona, D efflorescence on loess from Argentina, E and F from California.

Many hypotheses have been formulated to account for the nitrogen of South American deposits.[706] They have been postulated to have been

[706] Considerations of these various hypotheses are given by Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 254–260, Grabau, A. W., Principles of salt deposition, 1920, pp. 285–289; Penrose, R. A. F., jr., The nitrate deposits of Chili, Jour. Geol., vol. 18, 1910, pp. 1–32; Singewald, J. T., jr., and Miller, B. L., The genesis

derived from guano, from decomposition of great masses of algæ of lakes or sea, from decomposition of organic matter in soil, from bacterial fixation of atmospheric nitrogen, from mother liquors of salts deposited in the Andes, from atmospheric electrical discharges, from volcanic materials and activity, and from ammoniacal dust blown from the sea. The last stage in the formation of the Chilean nitrates seems to have been deposition following evaporation of ground water, although Sundt[707] has postulated origin in situ of some of the deposits, the nitrogen having been derived from the atmosphere and the sodium from decay of feldspathic porphyries.

The South American nitrates are best developed in northern Chili over the extremely arid lands lying between the Andes and the Pacific Coastal ranges, where they are associated with rock salt, the latter more extensive and on the lower areas. The nitrates generally are on the western and deeper margin of the desert plain between the mountains, where they are underlain by Jurassic volcanics and recent débris. Typical positions are the lower

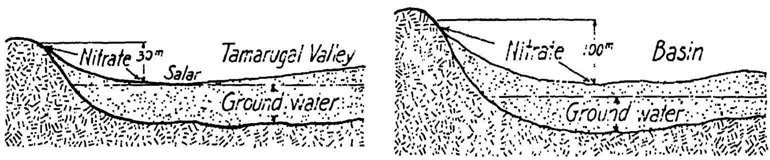

FIG. 62. IDEAL SECTIONS OF THE NITRATE DEPOSITS OF CHILI, (*1*) TARAPACÁ, (*2*) AGUAS BLANCAS

The dotted areas represent gravel, the dashed volcanic rock. After Whitehead, W. L., The Chilean nitrate deposits, Econ. Geol., vol. 15, 1920, p. 207.

slopes of the hills rising out of the plain and the terraces or slopes around the "salares," or salt flats, depressions in the desert plain characterized principally by rock salt with which are smaller quantities of sodium sulphate and the chlorides and sulphates of calcium, magnesium, and potassium, but no nitrates except on the Salar del Carmen in the Pampa Central. The nitrate deposits range from a few to perhaps a hundred feet above a "salar." Occasionally a deposit occurs over the bottom of a basin. All gradations of nitrates and other salts seem to be present. Figure 62 shows ideal relationships. The nitrate beds are known as "calitreras" and the

of the Chilean nitrate deposits, Econ. Geol., vol. 11, 1916, pp. 103–114; and with Sundt, L., Econ. Geol., vol. 12, 1917, pp. 89–96; Miller, B. L., and Singewald, J. T., jr., The mineral deposits of South America, 1919; Whitehead, W. L., The Chilean nitrate deposits, Econ. Geol., vol. 15, 1920, pp. 187–224. See also Singewald, J. T., jr. and Miller, B. L., Boletin de la Sociedad Nacional de Mineria, Nos. 244, 245, June, 1919.

[707] Sundt, L., op. cit., pp. 89–91.

crude nitrate as caliche. A general descending section of the nitrate deposits of the Tarapaca region is as follows:[708]

7. Gravel composed of small, polished, and angular rock fragments with little or no salt.
6. Sandy crystalline salt, dominantly sodium sulphate.
5. Hard, somewhat porous conglomerate of which the cement is sodium sulphate. This conglomerate is known as "panqueque."
4. Soft, white, fluffy sodium sulphate containing 10 to 15 per cent sodium chloride and traces of nitrate.
3. Sands and gravels cemented by salts containing less sulphate than 4, but more chloride and nitrate. This zone is known as "costra" and ranges in thickness to several feet.
2. Gravel cemented by salt with high nitrate content. This zone contains most of the minable ore and is known as caliche. The range in thickness is from a few inches to several feet. It usually forms a hard, compact bed which has a brown or buff color.
1. Fractured rock or gravel, uncemented, frequently containing high salt content, and then known as "congelo," otherwise known as "coba."

Below are stratified sands and gravels to various depths, or bed rock. Zones 4, 5, and 6 are known as "chucho" and range to several feet in thickness. Analyses of chucho, costra, and caliche are given in tables 71 and 72. It quite naturally follows that there is considerable variation.

As shown by the analyses, the nitrogen is mostly in the form of sodium nitrate. This generally occurs as a translucent mass, but it is also present as interlocking crystals, efflorescences, and some other forms. The pure nitrate is white, but impurities give many colors. The mined caliche usually contains 14 to 25 per cent sodium nitrate. Deposits approximating 50 per cent sodium nitrate are now seldom found in quantity.

Other nitrate deposits in South America are in Colombia, Bolivia, and Argentina. A deposit in Argentina lies within the Andes in a playa known as the Salinas Grandes. This deposit is 360 miles from the sea and at an elevation of 3500 meters, with the mountains around rising to 6000 meters. In the center of the playa, rock salt exists to a thickness of 20 to 30 cm. Around the borders of the salt are ulexite nodules, and other borax minerals are also present, suggesting contribution from volcanic sources. This playa is flooded in the spring time by waters from the mountains and is dry in summer. The deposit of one locality in Bolivia is also of interest, as it is composed of 60 per cent potassium nitrate and 30 per cent sodium borate ($Na_2B_4O_7$).

[708] Penrose, R. A. F., jr., op. cit., p. 14; Whitehead, W. L., op. cit., pp. 201–205.

TABLE 71

ANALYSES OF CHUCHO*

Soluble:		
CaO, MgO	14.3	15.3
K_2O	6.2	7.5
Na_2O	24.9	20.9
H_2SO_4	30.4	46.5
HNO_3	5.9	
Phosphoric acid	2.9	3.9
Iodic acid	0.3	
HCl	10.6	4.2
H_2O	4.7	2.1
	100.2	100.4
Insoluble	79.3	89.3

* Whitehead, W. L., op. cit., p. 202.

TABLE 72

ANALYSES OF COSTRA AND CALICHE*

	COSTRA*	CALICHE†
$NaNO_3$	13.6	22.73
KNO_3	1.3	1.65
NaCl	19.3	41.90
Na_2SO_4	6.7	0.94
$MgSO_4$	9.7	3.13
$CaSO_4$	2.7	4.80
$Na_2B_4O_7$		0.53
$NaIO_3$	0.1	0.07
NH_4 salts		Trace
Na_2CrO_4		Trace
H_2O	2.4	1.75
Insoluble	44.0	22.50
	99.8	100.00

The following minerals have been recognized in the caliche: anhydrite, gypsum, thenardite, mirabilite, bloedite, epsomite, glauberite, halite, darapskite ($NaNO \cdot Na_2SO_4 \cdot H_2O$), nitroglauberite ($6NaNO_3 \cdot 2Na_2SO_4 \cdot 3H_2O$), lauterite ($CaI_2O_6$), and dietzeite ($7CaI_2O_6 \cdot 8CaCrO_4$).

* Semper and Michels, Die Salpeterindustrie Chiles, Zeits. f. Berg. Hütt.-Salinenw. vol. 52, Abh., 1904, p. 8.

† Penrose, R. A. F., Jr., p. 14. D. G. Buchanan, analyst.

There has been considerable difference of opinion respecting the conditions and processes of origin of the South American nitrate deposits, but present

opinion seems to be practically unanimous in ascribing their deposition to ground-water action. The immediate factors responsible for their origin are the physiography and the extremely arid climate of the region, the latter leading to extreme evaporation and the former concentrating the underground and limited surface waters on the western edge of the desert basin. Singewald and Miller[709] assigned the nitrate deposits to "the accumulation, by means of evaporation, of the minute nitrate content of the underground waters of the region," the deposition of the salts representing "a sort of efflorescence." They point out that where the nitrate accumulates, the water table is not far from the surface, and they are of the opinion that capillarity brings some of the ground water thereto, where evaporation leads to deposition of the contained salts in the loose materials between the surface and the water table. The waters are thought to originate on the western slopes of the Andes, whence they drain through the materials of the desert basin to its deeper areas adjacent to the coastal ranges, there coming close to the surface and thus concentrating the contained salts in that portion of the desert. The nitrates are assumed to have been derived from the materials through which the ground water passed. Owing to the extremely deliquescent nature of the nitrates, they would tend to become concentrated in those parts of the western margin of the desert which are least moist, thus accounting for their occurrences in the lower portions of the sloping lands above the salars or salt flats.

Whitehead[710] questions the theory of Singewald and Miller and states that the depth of the water table and the nature of the overlying materials preclude capillarity from lifting the water so high and thus make the theory outlined above untenable. His theory differs chiefly from the above in that he holds that the waters of deposition are descending. The nitrate is derived from sources on steep slopes and hilltops and concentrated lower down on less steep slopes by dew, fog, and the occasional rains, the salts being stratified in accord with their solubilities. There is continuous removal from upper slopes and enrichment lower down and general migration of the entire deposit downward, so that finally the basin level may be reached. On first being taken into solution, descent is made to a surface less steeply inclined and thinly veneered with gravel, the first solutions to reach the upper gravel slopes being considered probably to be sodium nitrate because of the latter's deliquescent nature. These solutions penetrate the gravel, evaporate to some degree during the diurnal period of low humidity, and cement the materials penetrated. The occasional light rains dissolve the sulphates and chlorides left after removal of the nitrates, and these are carried

[709] Singewald, J. T., jr., and Miller, B. L., op. cit., 1916, pp. 107, 108.
[710] Whitehead, W. L., op. cit., 1920, pp. 210–216.

downward to lower slopes and deposited, possibly covering the previously deposited nitrate. The first deposits made on the upper gravel slopes are assumed to be thin beds composed of a mixture of sodium nitrate, sodium chloride, and sodium sulphate. The high humidity of cold nights may bring the relative humidity to 70 per cent, or that necessary to form a saturated solution of sodium nitrate. This sinks into the ground and moves downward on the slopes due to gravitation and capillarity. The succeeding low humidity and high temperature of day bring about deposition of the nitrate and of any sodium chloride and sodium sulphate in the solution. After this has been often repeated and the nitrate has been moved a considerable distance from the surface, a light rain may provide sufficient water to carry sodium chloride and sodium sulphate downward to be deposited in gravel above the nitrate. In this way the three characteristic zones of a nitrate deposit are formed: (1) the upper zone of the less soluble sodium sulphate, (2) the sodium chloride with sodium sulphate zone, and (3) the nitrate zone with its base at the greatest depth where porosity permits evaporation and deliquescence. Whitehead (pp. 216–222) favors the volcanic hypothesis as a source for the nitrogen.

The Whitehead explanation of the concentration of the nitrates seems reasonable, and if the ground-water level is as deep as stated by him and has always been so during the times of the accumulation of the nitrates, it does not seem that the explanation of Singewald and Miller is adequate.

Sodium nitrate occurs in the western United States under climatic conditions somewhat similar to those of Chili. In the Amargosa region of southeastern California it is found about 9 inches below the surface in a 5-inch layer of caliche which is mostly sodium chloride.[711] The nitrate content is, however, too low for commercial development.

Mechanical Deposits of Salts

Mechanical deposits of salts are composed mostly of gypsum and are usually of wind deposition, the particles having been derived from older gypsum deposits, from efflorescences of surface caliche, or other efflorescences about lakes and springs. Naturally, the deposits so far as they were derived from efflorescences would contain many salts besides gypsum, but if the region possesses any rainfall whatever, the more soluble would be leached out, leaving the gypsum fairly pure. Dunes of gypsum occur over an area of about 300 square miles in Otero County, New Mexico, the gypsum sand having been derived from older beds of gypsum within the region[712]

[711] Noble, L. F., Mansfield, G. R., etc., Nitrate deposits in the Amargosa region, southeastern California, Bull. 724, U. S. Geol. Surv., 1922.

[712] Herrick, C. L., The geology of the white sands of New Mexico, Jour. Geol., vol. 8, 1900, pp. 123–124.

(fig. 63). Similar sands on an apparently smaller scale are said to occur in Utah and Australia,[713] and small accumulations may be seen locally in any dry region possessing efflorescences on the surface or bedded deposits of gypsum. Wilder suggests that attention should be directed to this method of origin for some of the extensive gypsum deposits, and has described cross-laminated gypsum from Oklahoma which may have developed through wind deposition.[714]

FIG. 63. DUNES OF GYPSUM SANDS

Photograph of the dunes of gypsum sands near Alamogordo, New Mexico. The photograph was received from Professor Evan Just of the New Mexico School of Mines. The dunes are found over an area of about 10 by 30 miles.

Evaporation Deposits of Enclosed Basins

The saline residues of lakes depend on the waters of the regions, the nature of the country rock through which the waters flow, whatever their source, and the kinds of salts brought to the lakes by wind. In table 73 are given analyses of the waters of Great Salt Lake and some of its tributaries which illustrate the variations in the waters supplied and the result after concentration.[715]

The waters of enclosed basins show great quantitative as well as great qualitative variety in the substances in solution. This is shown by the analyses in table 74.

[713] Wilder, F. A., Some conclusions in regard to the origin of gypsum, Bull. Geol. Soc. Am., vol. 32, 1921, p. 389.

[714] Wilder, F. A., Gypsum, Mineral Industry, vol. 24, 1915, p. 371.

[715] Clarke, F. W., op. cit., Chap. V.

TABLE 73

	GREAT SALT LAKE, 1913	BEAR RIVER NEAR MOUTH	JORDAN RIVER NEAR SALT LAKE CITY	OGDEN RIVER, OGDEN, UTAH	WEBER RIVER NEAR MOUTH OF CANYON
Cl	55.48	32.36	34.76	23.21	13.73
SO_4	6.68	8.16	30.68	5.65	9.25
CO_3	0.09	21.53	Trace	33.68	40.00
Na	33.17	20.54	23.04	11.31	8.37
K	1.66			4.16	4.19
Ca	0.16	10.12	10.26	16.05	18.19
Mg	2.76	4.76	1.26	5.94	6.27
Al_2O_3, Fe_2O_3		2.53			
	100.00	100.00	100.00	100.00	100.00
Salinity permille	203.49	0.637	1.09	0.444	0.455

TABLE 74

	SODA LAKE, NEV.	OWENS LAKE, CALIF.	BORAX LAKE, CALIF.	DEAD SEA 120 M. DEPTH	LAKE DOMO-SHAKOVO, SIBERIA	LAKE TEKIR-GHIOL, ROUMANIA
Cl	36.51	24.82	32.27	67.66	3.71	60.53
Br			0.04	1.98	Trace	0.18
SO_4	10.36	9.93	0.13	0.22	63.62	0.67
CO_3	13.78	24.55	22.47	Trace	0.08	Trace
PO_4		0.11	0.02			
B_4O_7	0.25	0.14	5.05			
NO_3		0.45			0.07	
Li		0.03				
Na	36.63	38.09	38.10	10.20	30.61	34.78
K	2.01	1.62	1.52	1.62	0.59	1.68
Ca		0.02	0.03	1.51	0.58	0.28
Mg	0.22	0.01	0.35	16.81	0.74	1.84
SiO_2	0.24	0.14	0.01	Trace	Trace	0.01
Al_2O_3, Fe_2O_3		0.04	0.01		Trace	0.03
As_2O_3		0.05				
	100.00	100.00	100.00	100.00	100.00	100.00
Salinity permille	113.7	213.7	76.56	245.73	145.5	70.877

These waters are thought to be fairly representative of those of enclosed basins. The content differs from year to year, with different seasons of the year, and also with depth.

The salts are precipitated from the waters of enclosed basins through evaporation, freezing, and changes of temperature, the type of mineral depending on the process responsible for the precipitation and the conditions prevailing at that time. The illustration given in connection with the deposits made about springs shows the effects of freezing. The experiments of Ochsenius, Van't Hoff, and others, and occurrences in nature prove that temperature is an important factor. Thus, in winter the sodium sulphate mineral, mirabilite, is deposited in heaps on the shores of Great Salt Lake and undergoes partial solution during the summer months. A similar condition obtains on the shores of the Gulf of Kara Boghaz.

Most lakes have periods of inflow of greater or less quantities of fresh water, during which time they receive quantitative and qualitative additions to the salts already in solution, have their waters diluted, and may receive suspended matter to be spread over the bottoms to greater or less thicknesses. During dry seasons deposits of salts may be made. Lakes whose waters have concentration as high as those of the Dead Sea have calcium carbonate and calcium sulphate precipitated near the mouth of each stream which enters, as the lake waters are already too highly concentrated to hold these salts. Thus, the Jordan precipitates calcium carbonate and calcium sulphate where it enters the Dead Sea.

Many basins of arid regions are without water during parts of the year or over terms of years. Of this character are Searles, Soda, and other lakes of California. These are under water only after big rainfall, and at other times are desert playas covered with white salt,[716] most of which in Soda Lake is sodium sulphate.

The deposits of Searles Lake[717] rival those of Stassfurt in chemical interest. During the Pleistocene epoch of glaciation this lake had a depth of 635 to 640 feet. During and for a short time after wet seasons the central part is flooded to a depth of a few inches; at other times it is dry. The "lake" consists of a "central area of firm, crusted salt," covering 11 to 12 square miles, surrounded by an area of salt-encrusted mud and sand which is bare of vegetation and composed of alluvium washed from the surrounding uplands, the whole impregnated with salts to a greater or less degree. These two areas constitute the "playa zone," containing about 60 square miles.

[716] Arnold, R., and Johnson, H. R., Sodium sulphate in Soda Lake, Carrizo Plain, San Luis Obispo County, California, Bull. 380, U. S. Geol. Surv., 1909, pp. 369–371; Gale, H. S., Sodium sulphate in the Carrizo Plains, San Luis Obispo County, California, Bull. 540–N, U. S. Geol. Surv., 1914, pp. 429–433.

[717] Gale, H. S., Salines in the Owens, Searles, and Panamint Basins, southeastern California, Bull. 580, U. S. Geol. Surv., 1914, pp. 265–312; see also Grabau, A. W., Principles of salt deposition, 1920, p. 283.

The playa zone passes gradually into the surrounding alluvial fan and kindred deposits, and these merge with the rocky slopes of the bordering mountain ranges.

The salt crust over the central area is mostly halite, which is so firm that it will support a wagon and team and even a heavy drilling rig. Drilling shows it to have a thickness ranging to over 100 feet and probably averaging 70 to 75 feet for the main part of the deposit. The salt contains more or less terrigenous sediment deposited by dust storms. There is more or less stratification, the layers differing in physical characteristics and also in chemical composition, the latter shown in table 75. The salts are immersed in more or less mother liquor, whose movement is possible because of a cellular structure of the deposit, the brine being estimated to exceed 25 per cent of the volume. The hypothetical average composition of the anhydrous residue to the brine is as follows:

TABLE 75

DEPTH IN FEET	INSOLUBLE SAND, ETC.	NaCl	Na_2SO_4	Na_2CO_3	$NaHCO_3$	NaB_4O_7	H_2O	TOTAL
0–18	0.2	79.7	7.6	3.2	0.0	Trace	3.3	94.0
18–12	1.4	44.0	30.5	14.8	2.5	1.0	5.8	100.0
25–30	1.4	47.3	28.1	10.6	0.0	2.0	10.6	100.0
30–35	3.0	42.7	17.1	19.1	5.9	2.0	10.2	100.0
35–50	1.4	43.5	22.3	9.5	2.5	5.5	15.3	100.0
50–65	Trace	82.8	10.6	3.2	0.8	Trace	2.6	100.0
65–79	Trace	19.0	7.3	40.3	18.5	0.5	14.4	100.0

	Per cent
Sodium chloride	51.61
Sodium sulphate	19.22
Sodium carbonate	12.79
Sodium biborate ($Na_2B_4O_7$)	3.23
Potassium chloride	12.07
Sodium arsenate (Na_2AsO_4)	0.17
	99.09

The composition of the salts which the brine immerses is given in table 75, the samples having been acquired from a well drilled near the center of the main salt deposit. Other wells show different proportions of salts.

In general, the analyses of the salts from the different wells show a concentration of the carbonates and bicarbonates at the base of the deposit, particularly of the latter, and of sodium chloride at the top, and more or less continuous deposition of sulphate. The sequence and relations of the

different salts are in accord with results obtained by Chatard[718] from evaporation of waters of Owens Lake, situated a short distance northwest of Searles Lake, and leave little doubt that the salts of the latter are the deposits of evaporation of the natural drainage waters of the region. However, there is one fact worthy of note, and that is, the mother liquors do not lie on the surface of the salts already precipitated, but rather thoroughly permeate them.

Minerals recognized in the Searles deposit are: halite, mirabilite, thenardite, trona, natron, borax, gypsum, anhydrite, glauberite, hanksite, northupite ($MgCO_3 \cdot Na_2CO_3 \cdot NCl$), pirssonite ($CaCO_3 \cdot Na_2CO_3 \cdot H_2O$), gaylussite, sulphohalite ($2Na_2SO_4 \cdot NaCl \cdot NaF$), tychite ($2MgCO_3 \cdot 2Na_2CO_3 \cdot Na_2SO_4$), searlesite, soda niter, dolomite, calcite, celestite, and colemanite.[719]

Death Valley seems to be an ancient lake bed of the same class as Searles Marsh. In the very lowest part of the valley is an area several miles across which is usually a smooth field of snowy white salt. This portion occasionally is flooded by water. A well bored in the southern part of this valley gave the following section:[720]

	Feet
Salt	0.5
Clay, light brown, soft, containing crystals	3.5
Salt, very hard	2.0
Mud, soft, brown, containing coarse crystals	11.0
Mud, soft, brown	0.5
Salt, in layers 1 inch thick	0.5
Mud, soft, brown	3.0
Mud, light brown, containing crystals	3.0
Mud, soft, brown, containing crystals	3.0
Salt, hard	2.5
Clay, tough, brown	0.5
Salt, hard	1.0
Mud, soft, brown, containing crystals	0.3
Salt, hard	0.7
Clay, dark, containing crystals	4.5
Salt, hard	1.5
Mud, black, containing crystals and 1 inch beds of hard salt	1.5
Salt, hard, black	2.0
Mud, black, containing crystals	1.5
Salt, hard	0.2
Clay, black, containing crystals	2.3

[718] Chatard, T. M., Natural soda: its occurrence and utilization, Bull. 60, U. S. Geol. Surv., 1890, pp. 59–67.

[719] Gale, H. S., Salines in the Owens, Searles, and Panamint Basins, southeastern California, Bull. 580, U. S. Geol. Surv., 1914, pp. 265–312; see also Grabau, A. W., Principles of salt deposition, 1920, p. 283.

[720] Gale, H. S., Prospecting for potash in Death Valley, California, Bull. 540, U. S. Geol. Surv., 1914, pp. 412–413.

	Feet
Salt, hard, black	0.5
Clay, light gray and black mixed, containing crystals	5.0
Salt, very hard	1.5
Clay, dark, containing crystals	0.5
Salt, hard	0.5
Clay, tough, dark	0.5
Salt, black, very hard	15.5
Clay, dark blue, containing crystals	1.0
Salt, very hard, black	5.0
Clay, dark blue, containing crystals	2.5
Salt, hard, black	1.0
Clay, dark blue, containing crystals	6.2
Salt, hard	1.0
Clay, dark blue, containing crystals	3.8
Salt, very hard	1.5
Clay, dark blue, very tough, containing crystals	4.0
Clay, black, tough, containing crystals	8.0
	104.0

This gives a total of 37.4 feet of salt out of a total of 104 feet. The alternation of salt and mud or clay can hardly be seasonal and probably indicates irregular intervals of varied duration. The crystals of salt in the clay may have formed there during deposition or subsequently.

In Funeral Mountain on the east side of Death Valley in Tertiary sediments there is a deposit of colemanite which outcrops for at least 25 miles. It is not a regular bed, but consists of irregular masses of colemanite through a thickness of 20 feet of clay. The same region is reported to have a 60-foot bed of boracite.[721]

Among the deserts of central Asia is one in the basin of the Tarim River known as the Takla-Makan. In this desert is the extensive salt plain of Lop in the lowest part of which is the contracted salt lake of Lop-Nor or Kara-Koshun. The desert is surrounded by lofty mountains, has low precipitation, and great extremes of temperature. The salt plain has a length of 200 miles and a width of about 50 miles at its broadest place. The salt is very hard, and its surface is described by Huntington[722] as "resembling the choppiest sort of sea, with white caps a foot or two high, frozen solid." The salt deposit is that of an extinct lake. After the salt became dry it broke up in the manner of mudcrack polygons into "pentagons" from 5 to 12 feet in diameter. These cracks filled with dust into which capillary action brought salt from below. The crystallization of this salt and perhaps other processes buckled the polygons and thus gave rise to the rough surface. Locally the surface of the salt plain is smooth, and in these places the salt

[721] Campbell, M. R., Bull. 213, U. S. Geol. Surv., 1902, p. 404.
[722] Huntington, E., Pulse of Asia, 1907, Chapter XII and pp. 251–252.

rests on soft oozy mud which is evidently impregnated with bittern. The salt appears to have been brought into the extinct lake by streams draining the surrounding region.

In the early stages of a salt lake's history its water is likely to be inhabited by organisms, but when deposition of salt sets in, these begin to disappear and the final deposits are scanty in organic remains except as they are brought in by draining streams or blown in by wind, or as occasional terrestrial organisms become mired in the lake's muds.

As salt lakes are in desert regions, it frequently happens that the waters receive large quantities of dust from the atmosphere. This dust consists chiefly of the fine products of rock disintegration, but it may also contain matter derived from the efflorescences formed on the desert's surface. Some of these will go into solution unless the waters are already saturated therewith. The terrigenous material settles to the bottom and gives rise to a layer of clay, and the matter brought in suspension by streams gives rise to other beds of clay. There thus may be clays of two types of history in the deposits of salt lakes, one made during the dry season and the other during the season of rainfall. Data for differentiation have not been established, but the clay brought in by the streams should grade into more coarse materials toward the mouths of the streams, whereas that due to wind deposition should have uniform character and thickness over the entire basin.

As a lake grows smaller through evaporation, the waters become concentrated in the lower parts of its basin where the normal succession of deposits form. The more insoluble and first-precipitated substances will have more extensive distribution than the more soluble, whose deposition will be largely confined to the lower and probably more central area of the basin. However, many of the first-deposited salts may be redissolved and carried to the central basin to attain redeposition. Finally, evaporation would leave nothing except the mother liquor, and this, in accord with the conditions of the Searles Lake deposits, would permeate the already deposited salts, with its further evaporation retarded by the heat reflected back to the atmosphere from the whiteness of the surface salts. Drifting sands or dusts, on the other hand, might overwhelm the basin and bury the whole. The mother liquors might then travel to the surface by capillarity, to be evaporated and deposit their salts among the sands or dusts; and where the salts reached the surface, they might be scattered by winds.

From what has been stated in preceding paragraphs, it seems that the deposits of a desiccated salt lake would have lenticular form, with bordering salts less soluble than the central portion, and the latter mainly composed of rock salt, but containing a rather wide range of salt minerals. Muds of

the character shown in the Death Valley section are likely to be present at various levels, particularly in the marginal portions.

In preceding paragraphs it has been assumed that the salts of salt lakes have been acquired from surrounding areas by the normal drainage of the region. It may be that this is not always the case. Holland[723] has offered an interesting and seemingly very valid explanation of the origin of the salts of some salt deposits made in the desert lake of Sambhar of the Rajputana Desert, northwestern India. He has proved that salt is carried as dust during the times of the southwest monsoon, the salt being derived from the Cutch region to the south and west. Analyses of the air showed that at least 3000 metric tons are carried over Sambhar Lake during one dry season and that 200,000 metric tons are annually carried into the Rajputana States. This salt dust is partly dropped over the desert and partly held in the atmosphere. During the rainy seasons it is washed from the atmosphere and from the surface of the desert and carried to the low places, where evaporation during each succeeding dry season leads to its deposition.

Grabau[724] has suggested that the Salina salt deposits of New York and adjacent regions developed in a body of water akin to a desert lake. He postulates the salts to have been contained in the Niagara limestones and to have come to the surface as efflorescences as the limestones decomposed and disintegrated under conditions of aridity then and there existing. These efflorescences were then washed, or blown, into the deeper portions of the Salina basin, where evaporation led to deposition of the salts contained in solution. The efflorescences are postulated to have been largely sodium chloride, and any calcium sulphate is supposed to have largely been left in the rocks of derivation, so that gypsum was not deposited except as scales and crystals in sands and muds. The products of the disintegration of the Niagara limestones are assumed to have occasionally been washed or blown into the basins in which the salt was deposited, and to have formed the beds of fine-grained limestone interstratified with the salt beds. This complex hypothesis accounts for deposition of salt without gypsum below (the gypsum at that time not believed to hold such stratigraphic relationship). But, as pointed out by Alling[725] and Newland,[726] the supposed relationship is doubtful and certainly incorrect in some cases, making several of Grabau's assumptions unnecessary. Few fossils occur in the salt and

[723] Holland, T. H., The origin of desert salt deposits, Proc. Liverpool Geol. Soc., vol. 11, pt. iii, 1912, pp. 227–250.

[724] Grabau, A. W., Comprehensive geology, pt. ii, 1920, pp. 340–343.

[725] Alling, H. L., The geology and origin of the Silurian salt of New York State, Bull. 275, New York State Mus. 1928, p. 75.

[726] Newland, D. H., Recent progress in the study of the Salina formation, Rept. Comm. Sedimentation, Nat. Research Council, 1928, pp. 36–43.

associated beds, and this has been construed into an argument that the Salina basin lacked connection with the sea, but this argument also fails of validity. Considerable gypsum, or anhydrite, lies above the sodium chloride. It was Dana's[727] view that the gypsum of the Salina basin resulted from the alteration of limestone, and Grabau[728] has concurred with him. However, there is considerable doubt that this is the correct interpretation, and neither Alling[729] nor Newland,[730] who have studied these deposits probably more thoroughly than earlier students, is in accord with this assumption. While not dissenting from the origin of local occurrences of calcium sulphate from limestone, each holds, particularly Newland, that the sulphate deposits are mainly of primary deposition.

Evaporation Deposits of Marine Waters

Evaporation deposits from sea water are made where arms or parts of the sea have been partially or completely cut off from the main body through crustal movement, or by the building of bars. The arm may receive additions of sea water regularly through an opening in, or seepage through, the barrier, occasionally through flooding over the barrier, or the separation may be so complete that no additions whatever are received.

Following Grabau,[731] water bodies containing sea water in which precipitation of salt may occur may be divided into the four classes of marginal salt pans, marine salinas, lagoonal deposits, and cut-off portions of the sea with complete or nearly complete separation.

Marginal Salt Pans. Salt pans exist near the mouth of the Indus in the Rann of Cutch, on the Red Sea coast, on the Nile Delta, on the Black Sea coast over the flat delta plains of the Danube and Dneiper regions, and on a small scale on many other coasts. The Rann of Cutch is the largest and is typical.

The Rann of Cutch is a low plain lying inland from, and on both sides of, the Island of Cutch south of the mouth of the Indus. The region is arid and the plain is mantled with sand plentifully impregnated with salt. The surface is always moist, and occasional pools of salt water are present. It has a width of about 60 miles, a length exceeding 180 miles, and an area of about 7000 square miles. The Rann merges laterally into the Put, the surface of which is flat and dry and which is margined by a sand-dune region known as the Thurr. The heights of the dunes range to nearly 400

[727] Dana, J. D., Manual of geology, 4th ed., 1895, p. 554.
[728] Grabau, A. W., Principles of salt deposition, 1920, p. 357.
[729] Alling, H. L., op. cit., p. 91.
[730] Newland, D. H., op. cit.
[731] Grabau, A. W., op. cit., pp. 116–122.

feet, and lakes locally lie between them. There is no vegetation in the Rann and Put, apparently no life of any kind in the Rann, and no fresh water anywhere in the region. During the times of the southwest monsoons the Rann is flooded to a maximum depth of about a meter; during the northeast monsoons this water flows back to the sea so far as it is possible; a part of it, however, soaks into the ground or is held in pools, but in either case the water ultimately evaporates and deposits crusts of salt. These crusts average about 10 cm. in thickness, but may exceed a meter.

A salt pan on the Nile Delta near Alexandria receives from 7 to 14 cm. of large, intergrown crystals of well bedded salt each year, the salt deposits resting on a black slime filled with organic material. When dry, the surface of the pan becomes broken up into polygons separated by ridges of salt from 5 to 30 mm. in height. The brine of this pan contains small crustaceans of red color, and these color the salt.[732]

Deposits formed in a salt pan obviously cannot reach a great thickness so long as the original surface of the pan remains stationary with respect to sea level, but if sea level should gradually rise it would be possible for salt to accumulate to a thickness closely related to the extent of such rise. This salt would consist of thin units, each deposited annually, and composed of calcium carbonate, calcium sulphate, sodium chloride, and other compounds. There would be essentially no development of mother-liquor salts. Salts of this origin ought also to contain marine organisms, as the pans periodically receive waters directly from the sea.

MARINE SALINAS. Marine salinas are those bodies of water adjacent to a sea coast which receive sea water by seepage through a separating sand or gravel barrier and have no or very slight inflow of fresh water. Deposits appear to be possible only on arid coasts. The best example is a sea-coast lake on the Island of Cyprus in the eastern Mediterranean[733] (figs. 64, 65). The basin has an area a little greater than 2 square miles, and its greatest depth is only about 3 feet. The surface of the water in the lake averages 10 feet below sea level in summer and 7 feet below in winter. The barrier is about 1.5 miles wide and consists of unconsolidated sands, clays, and shell matter resting on impervious clay. Evaporation exceeds inflow during summer, and a crust of salt is formed over the bottom of the basin. Another example of this type of basin is Lake Tekir-Ghiol in Roumania, which is separated from the Black Sea by a barrier about 1000 feet wide. An analysis of the solid content of the waters of the lake is given on page 488.

[732] Grabau, A. W., Principles of salt deposition, 1920, pp. 120–121. Walther, J., Das Gesetz der Wüstenbildung, 2nd ed., 1912, pp. 241–243; 4th ed., 1924, pp. 305–306.

[733] Bellamy, C. V., A description of the salt lake of Larnaca, Quart. Jour. Geol. Soc., vol. 56, 1900, pp. 745–758.

The deposits of marine salinas could contain marine fossils only in case waves passed over the barrier, as they might do in times of storm, or in case they were carried in by other animals. A lake of this kind is probably

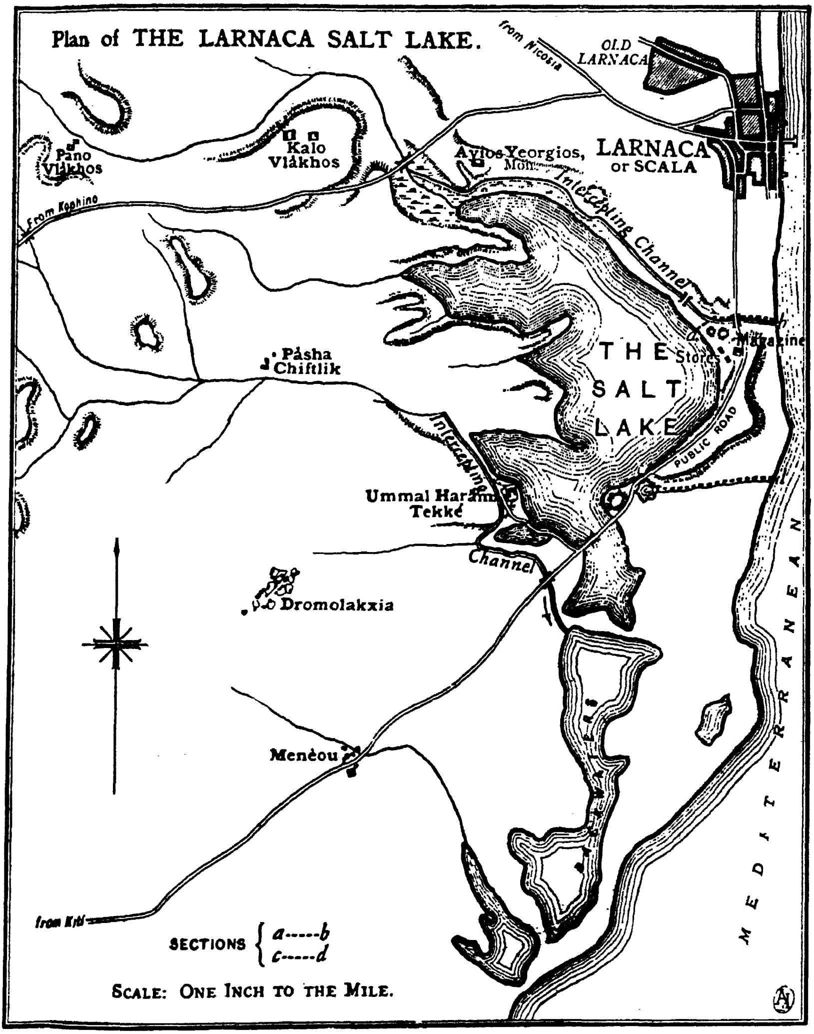

FIG. 64. OUTLINE MAP OF THE SALT LAKE OF LARNACA, ISLAND OF CYPRUS

The map shows the position of the lake with respect to the Mediterranean and the bar which separates the lake from the sea. A cross section of bar is shown in figure 65. The intercepting channels were constructed to decrease the inflow of fresh water and thus make the lake more valuable for the extraction of salt. After Bellamy, C. V., Quart. Jour. Geol. Soc., vol. 56, 1900, pl. 39.

only an incident in the history of a coast, and the deposits could hardly be other than of small extent and thickness. Mother-liquor salts might be deposited, but the probabilities are not great. Deposits of this origin may occur in the geologic column, but none has been recognized.

LAGOONAL DEPOSITS. Lagoonal deposits are made in basins marginal to the sea into which a current flows from the main body to restore that lost in the lagoon through evaporation. The requirement for their origin is that evaporation should exceed accretions from streams or precipitation, thus requiring additions from the main body to maintain level. This is a not uncommon condition, and such lagoons precipitating salts are by no means rare. Thus, lagoons back of islands on the eastern coast of Mexico are depositing salts, although connections with the waters of the Gulf are not greatly restricted.[734] The lagoonal theory, as outlined by

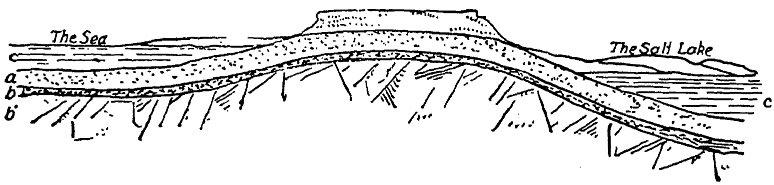

FIG. 65. CROSS SECTION OF THE BARRIER SEPARATING THE SALT LAKE OF LARNACA FROM THE SEA

The upper portion of the barrier consists of sands, gravels, and shell matter, this forming the layer designated *a* and what is above. These sediments are succeeded downward by clays of various character. The beds containing shells, sands and gravels extend to a depth below the shore of the lake of about 10 feet. The level of the lake approximates about 7 feet below the level of the sea and the deepest part of the lake is estimated at about 10 feet below mean tide level. *a* = Permeable strata (sands and conglomerates). *b* = Impermeable stratum (clay). *b′* = Layer of watery matter. After Bellamy, C. V., Quart. Jour. Geol. Soc., vol. 56, 1900, pl. 39.

Ochsenius,[735] postulates an arm of a sea, or the ocean, connected with the main body by an opening sufficiently large to permit inflow of water, but not deep enough to permit circulation, so that water entering the arm largely remains there except as removed by evaporation. A region is required with climate sufficiently arid to prevent inflow of fresh water into the arm, or to decrease it to a quantity below that removed by evaporation, so that the level of the bay must be maintained by additions over the barrier. The barrier may be made by waves or result from crustal movement, but a barrier of the latter type might develop a basin of the character of a relic

[734] Baker, C. L., Depositional history of the Red Beds and saline residues of the Texas Permian, Bull. 2901, Univ. Texas, 1929, p. 27; Pan-Am. Geol., vol. 52, 1929, p. 346.

[735] Ochsenius, C., Die Bildung der Steinsalzlager und ihrer Mutterlaugensalze, Halle, 1877; Beiträge zur Erklärung der Bildung von Steinsalzlagern und ihrer Mutterlaugensalae, Acad. Nova Acta, vol. 40, 1878, pp. 121–166.

sea. The thickness of deposit in a lagoon would be measured by depth of water, a great depth favoring a thickness related thereto. As the inflowing current brings additions of salts, the salinity of the water constantly increases, and ultimately the concentration essential for the precipitation of calcium sulphate is reached. When this concentration exists throughout the lagoon, calcium sulphate is precipitated in maximum quantity in that portion of the lagoon adjacent to the entrance through the bar, and sodium chloride and other salts might be deposited over portions of the bottom remote from the bar. A long-time closure of the entrance to the lagoon might lead to deposition of all the sodium chloride, which would rest on deposits of calcium sulphate of considerable thickness adjacent to the bar, and on thin deposits of that salt in more distant parts of the lagoon, and it is possible that places might exist where no gypsum existed beneath the salt. Finally, mother-liquor salts might be deposited. Cutting of the bar would renew connection with the sea, and the cycle would be repeated. Depression of the locality of the lagoon with respect to sea level—hardly likely for a small area—would permit long existence of a lagoon and hence extensive accumulation which might be entirely gypsum adjacent to the entrance and at the base, mixed or dovetailing salt and gypsum farther from the entrance, and essentially pure sodium chloride in remoter parts of the lagoon.

Ochsenius gave the Gulf of Kara Bogaz (fig. 66) on the east side of the Caspian Sea as a modern illustration of the lagoon theory of salt deposition. The Caspian is a relic sea, as shown by the character of its fauna, and is a remnant of a once much larger body of water. Rivers have given it large additions of salts since its separation from its parent body, and there has been an excess of evaporation over inflow and precipitation, as its surface is below sea level. Nevertheless, its salinity is lower than that of the Mediterranean or the ocean. This arises from the fact that a current flows from the Caspian into Kara Bogaz, with the result that the Caspian has a position analogous to that of a lake with outlet. Analyses of the solid contents of the waters of the Caspian and the Gulf of Kara Bogaz are given in table 76.[736] The low calcium content in the Gulf is accounted for by the fact that neither calcium carbonate nor calcium sulphate can be held in solution, and both are precipitated shortly after entering the Gulf.

The barrier separating Kara Bogaz from the Caspian is wave-made and consists of two sand spits. The Gulf is about 95 miles long and about 80 miles wide; the depth is not over 15 meters. Its waters are estimated to have in solution 34,000,000,000 million metric tons of salt, and 350,000 tons are estimated to be brought into it daily.[737]

[736] Clarke, F. W., op. cit., p. 169.
[737] Grabau, A. W., Principles of salt deposition, 1920, footnotes p. 132.

Gypsum is deposited in quantity along the shores of the opening into the Gulf and for some distance beyond the opening. During the winter months the water is saturated with respect to sodium sulphate, but not the chloride,

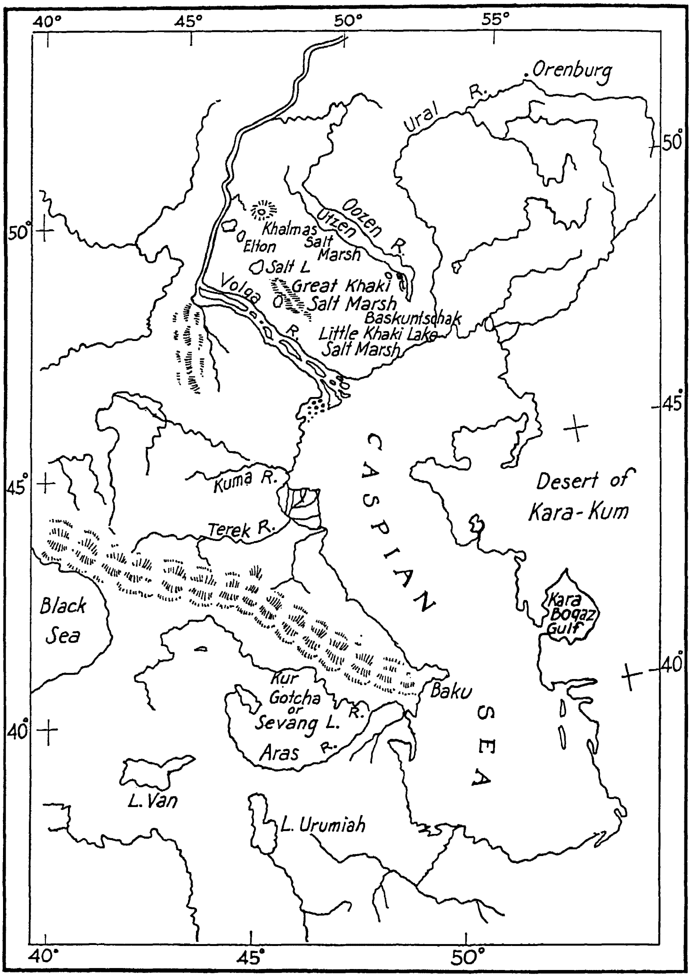

FIG. 66. OUTLINE MAP OF THE CASPIAN SEA AREA

The map shows the outlines and position of the Gulf of Kara Boghaz and the position and extent of the salt plains of southern Russia. After Grabau, A. W., Principles of salt deposition, 1920, p. 130.

and at that time deposits of glauberite are made in the shallow waters and toward the center, the area of such deposits being estimated at around 3500

square kilometers and the quantity of this salt at 1000 million metric tons. In summer the thickness averages about 1 foot, but it is thicker in winter. Rock salt is not deposited in the Gulf.

Many organisms are carried into the Gulf, where most of them stay to meet death, the only chance of escape existing for such of the nekton as are able to swim against the current. According to Andrussow,[738] the number of organisms thus killed is extremely large, and they can be found floating on the surface and piled along the shore, the greatest number being in fall and spring. Much organic matter must thus be incorporated in the salt which is being deposited, and it may be expected that fossils should be common, and even abundant, in salt deposits of lagoonal origin.

TABLE 76

	CASPIAN SEA	GULF OF KARABOGAZ
Cl	41.78	50.26
Br	0.05	0.08
SO_4	23.78	15.57
CO_3	0.93	0.13
Na	24.49	25.51
K	0.60	0.81
Ca	2.60	0.57
Mg	5.77	7.07
	100.00	100.00
Salinity permille	12.67	163.96

A salt deposit which has been assigned to a lagoonal origin[739] was discovered in the building of the Suez Canal, where it passed through the Great Bitter Lake of Suez. The Canal exposed a deposit of salt 8 miles long and 4 miles broad with an average thickness of about 25 feet. In the center of the lake the thickness was about 60 feet. The deposit was composed of layers of rock salt and gypsum separated by layers of earthy matter and small crystals of gypsum. A thickness of 2.46 meters ($8\frac{2}{3}$ feet) had 42 layers of salt and gypsum, the latter ranging in thickness from 3 to 18 cm. Between the layers of salt and gypsum were clay layers a few millimeters in thickness, which, as a rule, contained abundant remains of organisms still living in the Red Sea. Separation of Great Bitter Lake from the Gulf of

[738] Andrussow, H., Der Adschi-darja oder Karabugaz Busen, Petermann's Mitth., Bd. 43, 1897, p. 29; Grabau, A. W., Principles of salt deposition, 1920, pp. 131–139.

[739] Grabau, A. W., op. cit., pp. 139–142.

Suez is thought to have occurred some time after 600 B. C., the separation being caused by the building of a bar which prior to its permanently reaching the surface was exposed at low tide and possibly during occasional storms. It is possible that it was during such a time of exposure that Moses and his followers crossed the Red Sea to escape Pharaoh and his hosts. The occurrence of fossils in the clay layers points to decreased concentration and entrance of waters and sediments from the sea, and at the same time there would be removed mother liquors left from the salts already deposited. Such mother liquors at the time of cutting of the canal were found to be of far less quantity than was demanded by the salts already deposited. It would seem that entrance of the sea in large volume would be a frequently recurring event in lagoonal history, and that a lagoonal deposit would not often reach the stage of mother-liquor salt deposition. Walther[740] has suggested that the only chance mother liquors of lagoonal or other waters have to become evaporated would be brought about by burial beneath hot desert sands. Capillarity might then bring the mother liquors to or toward the surface, and in the former case they might become dissipated by winds, perhaps to be later concentrated in depressions between dunes and buried there.

A possible Miocene example of a lagoonal salt deposit is that of Wieliczka in Galicia. This is abundantly fossiliferous, carries no mother-liquor salts, and seems to have been formed in close association with the Miocene sea of southern Europe.[741]

A summary of the characteristics of salt deposits of lagoonal origin indicates that: (a) they are not likely to, but may, have large extent; (b) they are formed in close association with marine conditions; (c) they should contain marine fossils in abundance; and (d) they do not, as a rule, contain mother-liquor salts.

The facts that there are many salt deposits without underlying gypsum and many gypsum deposits without beds of limestones below, and that many salt and gypsum deposits do not contain fossils, led Branson to postulate the occurrence of two or more basins[742] in the first of which the marine or stream organisms were killed and their remains buried or destroyed and the calcite and perhaps the gypsum precipitated. The waters attaining the second lagoon, after having deposited their calcium sulphate in the first lagoon, would deposit sodium chloride and other salts in succeeding lagoons. This hypothesis of a number of connecting lagoons marginal to a sea coast

[740] Walther, J., Das Gesetz der Wüstenbildung, 4th ed., 1924, pp. 311–312.

[741] Grabau, A. W., op. cit., 1920, p. 142.

[742] Branson, E. B., Origin of thick salt and gypsum deposits, Bull. Geol. Soc. Am., vol. 26, 1915, pp. 231–242.

or basins in an arid region requires a nice balance of conditions which probably did not often occur during earth history, and it is not likely that many very extensive deposits developed in this way. A modification of the theory will be considered in connection with the deposits of relic seas.

SALT DEPOSITS OF RELIC SEAS. Relic seas lie in large, deep basins which at one time had connection with a sea or the ocean and became separated therefrom through diastrophic, volcanic, or depositional processes. It is not likely that such separation has commonly been caused by volcanic processes, but each of the other two probably has produced relic seas. In the beginning of a relic sea's history as such, its waters were of the same character as those of the parent body, and for a long period of time, connection therewith through a continuously decreasing opening probably was maintained. Relic seas may contain either fresh or salt water, depending upon the rainfall and evaporation of the surrounding regions. If more water is lost by evaporation than is introduced by rainfall and flow of streams, the waters are salty, with a concentration determined by the aridity and other factors. After separation is complete, the surface of a salty relic sea will fall below sea level.

The Salton Sea of southern California is a relic sea severed from the Gulf of California by the building of the delta of the Colorado River. It is not, however, a good illustration of the condition thought to be essential for the development of extensive salt deposits, as the sea is close and the Colorado occasionally breaks into the basin to bring in fresh water. The Caspian Sea is a better illustration. This sea at one time was much larger and was reduced by evaporation to form the existing body of water. The level was lowered, and it now stands 84 feet below sea level. The abandoned part of its basin has over twenty-five hundred lakes and playas in which salts are being deposited and into which salts formerly deposited in the sediments around these lakes and playas are being washed. The salts formed during seasons of strong evaporation consist of sodium chloride and some of the bitter salts. During wet seasons the more soluble bitter salts are dissolved, and sodium chloride and calcium sulphate are left. The Caspian is less salty than the ocean, because of accessions of fresh water on the western side from the Volga and other rivers and the flow from the Caspian on the eastern side into the Gulf of Kara Bogaz. If the Caspian did not have this Gulf, was surrounded on all sides by arid conditions, had no contributing rivers of significance, was connected with the ocean by a narrow and shallow opening, and was subject to evaporation in excess of all contributions of fresh water, sea level would have to be maintained by additions through the opening from the ocean, and as concentration became great, calcium carbonate would be precipitated near the entrance, calcium sulphate far-

ther therefrom, and sodium chloride would be deposited over the remoter parts of the basin.[743] Accessory basins to the Caspian, as isolated bays and sounds, might receive deposits of bitter salts. Ultimately separation from the parent body would lead to shrinkage and lowering of the waters, and these might become restricted to several areas in the lower parts of the basin, in each of which the concentration would be high and possibly different. Deposits made in higher parts of the basin would be subject to removal through action of occasional rainfall and ground water. Only the more soluble salts would be likely to be removed, whereas such salts as calcium sulphate would be left. Removal of the soluble salts would increase the concentration in the shrunken waters, and finally a very thick deposit of sodium chloride and possibly of mother-liquor salts would result. Ultimately a relic sea might almost completely disappear, to become a playa or group of playas into which briny waters would be brought during times of rainfall to deposit their salts above those previously made, so that beds of rock salt, gypsum, and anhydrite would come to hold an apparently abnormal place in the sequence.

A relic sea owing its origin to diastrophic action might be expected to change position to some degree, and after having attained concentration essential to sodium chloride precipitation, to have been moved by warping over areas not previously occupied, and this would lead to deposits of sodium chloride over such areas with no calcium sulphate below. Again, the basin might deepen during and after its restricted connection with the ocean, thus making accumulation possible to a thickness related to the extent of deepening.

Fossils would be present in the deposits of a relic sea while connection with the ocean existed, and about places of inflow of fresh water, but after a degree of concentration had been attained prohibitive to most organisms, the organic matter would not be likely to extend a very great distance beyond the entrances and the mouths of streams. Hence, fossils should not be common in salt deposits made at some distances from the openings and inlets.

As diastrophic processes do not always seem to move in the same direction, but to fluctuate, with longer or shorter swings about a mean—in this case sea level—it is possible that connection of a relic sea with the ocean might be one or more times renewed, thus permitting something of a cyclic arrangement of the salt and associated deposits.

A large relic sea would be subject to a variety of conditions, due to temperature, variations in salinity, local influx of fresh water, influx of sediments,

[743] The reader should consult Baker, C. L., Depositional history of the Red Beds and saline residues of the Texas Permian, Bull. Univ. Texas, no. 2901, 1929, pp. 28–32, 41–47.

variations in depth, etc., and these would produce variations in the order and time of precipitation and character of the salts deposited, leading to lateral variation in the salt beds and to their splitting due to introduction of a wedge of clastic sediments. If such seas were of great depth, density stratification would be likely to obtain as exists in the Dead Sea at the present time in which the salinity ranges from 19 per cent at the surface to 26 per cent at the depth of 1000 feet. This might lead to the deposition of one variety of salt in the deeper waters and others in those of less depth. A similar qualitative variation would be likely to take place in deep lakes.

It is believed that the general conditions of environment outlined in the preceding paragraphs of this topic serve to account for the extensive and thick salt deposits of the geologic column, and it does not seem possible to account for these by any of the other conditions described. Bodies of water as deep as the thickness of the salt and associated sediments are not required. The characters of the sediments do not permit assumption of great depth, and it is not necessary to assume that the depositing waters were deep at any time. Hundreds and even thousands of feet of evaporites in a vertical section, such as exists in the Permian basin of west Texas, of course signify that most of these accumulated below the profile of equilibrium determined by the conditions, but it seems probable that the accumulation took place in a subsiding basin in which the waters were shallow at all times.

Extensive and thick salt and gypsum formations are commonly stated to carry few fossils, and this is as it should be if these are the deposits of relic seas, but the reported absence rests partly on traditional ideas suggesting that fossils should not be present, on careless observation based in part on assumption of absence, on insufficient collecting and observation, and on actual absence, not necessarily because organisms were never present in the depositing waters, but possibly because of corrosion in the brines.

It is suggested that the great salt deposits of the Permian of both the western United States and Europe developed in basins of relic seas. In the United States during the Permian the region of Kansas and some of the adjacent states was more or less cut off from the ocean to the southwest by the various mountains across southern Oklahoma. It is known that gypsum and anhydrite were deposited over the eastern and southern margin of this basin in some instances before the deposition of sodium chloride and also contemporaneous with and subsequent thereto. The stage for the deposition of the mother-liquor salts does not seem to have been reached in Kansas and Oklahoma, but polyhalite and other potash minerals are known to have been deposited in the Permian basin of western Texas. This Texas basin is also thought to be of the character of a relic sea, but the place of its con-

nection with the parent body is not yet established. Baker,[744] who has studied these Texas Permian strata, postulates an opening between the Glass and Guadaloupe mountains of Trans-Pecos Texas and possibly another farther north to connect with California waters. Into this relic sea were flowing fresh waters from rivers, thus keeping portions of the Permian basin of sufficiently low salinity to permit marine organisms to thrive, either generally over an area or in the surface waters in those places where low salinity permitted them to float over more saline waters beneath. The basin was large, thus making possible great variations in salinity and the deposition of different varieties of salts at different places. It either was very deep when the deposition of saline residues began, or subsided during deposition to permit accumulation of eight to ten thousand feet of strata. The surrounding region was not necessarily one of great aridity, but conditions over the basin were such that the quantity of water evaporated exceeded that supplied by precipitation and the inflowing streams, thus compelling contributions from the ocean.

Fossils are present in strata below, between, and over the salt beds. These relations suggest, in general, lessening of the salinity of the waters, for the fossils above and between the salt beds. In some localities sodium chloride beds are said to occur without underlying calcium sulphate. This has been explained for Kansas by Haworth[745] as due to warping of the basin by crustal movements so that concentrated waters flooded areas which previously had been exposed.

In Europe the Variscian (Hercynian) uplift toward the close of the Pennsylvanian raised high mountains across central Europe, which separated the northern basin from the Atlantic to the west and the Mediterranean to the south, making connection with the open sea over a somewhat devious and distant passage to the east. At the same time the Germanic basin became more or less dry or arid, with evaporation exceeding precipitation. It is postulated that a high concentration was attained before complete separation from the ocean took place, so that an abundance of mother-liquor salts was present in solution, a part of which ultimately became deposited in the deeper parts of the Permian basin.

In several parts of the world the rocks contain salt domes whose origin for a long time was a subject of considerable difference of opinion. At the present time it seems probable that the domes represent beds of salt which under the influence of pressure have flowed and risen in the form of domes or plugs into overlying beds, the latter being more or less arched by the

[744] Baker, C. L., Depositional history of the Red Beds and saline residues of the Texas Permian, Bull. Univ. Texas, no. 2901, 1929, pp. 9–72.

[745] Haworth, E., Mineral resources of Kansas, 1893, p. 89.

rising salt, or rising because of the pressure and thus inviting the salt to enter. Cause and effect are more or less interrelated, so that separation is difficult. The finding of fossil algæ in the Markham salt dome of Texas[746] proves that this dome was so formed, and, inferentially, all others. Hence, from the point of view of sedimentation, the salt domes involve nothing other than the formation of extensive and thick beds of salt.

Alteration Deposits of Salt

Gypsum is the most common salt which is formed to any significant extent through alteration, although considerable celestite and perhaps sulphur may also develop in this way. Wherever waters carrying sulphuric acid come into contact with limestone, the latter is changed to hydrated calcium sulphate. That this has gone on to a considerable extent seems demonstrated, and it is known to be occurring in some places at the present time, but it does not appear possible that bedded deposits of gypsum of wide distribution can thus be explained. The gypsum deposits of New York, where they lie above the salt beds, were postulated by Dana to have originated in this way, although this does not seem probable.[747] Wilder has also directed attention to gypsum deposits[748] which he inferred to have had this origin. It should not be difficult to differentiate such replacement deposits from those of other origin, as there should be many places where they show gradation to limestone, and they should contain patches of unreplaced limestone.

Potash, Soda, and Sodium Chloride of Organic Origin

That potash is present in many plants is attested by the lye or potash from the ashhoppers of American pioneer days. Certain plants contain considerable potash and iodine and others contain soda. For the sake of completeness these are considered in this connection.[749]

The giant kelp of the Pacific Coast is among the most important of the plants secreting potash and iodine. Analyses of the ash of three species of these kelps are given in table 77.

Potash is almost universally present in the ash of all vegetable matter. The ash of corn cobs has been found to contain as much as 20.13 per cent of water-soluble potash, as well as 4.01 per cent phosphoric acid; gooseberry

[746] De Golyer, E., Discovery of potash salts and fossil algæ in Texas salt dome, Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, pp. 348–349.

[747] Dana, Manual of geology, 4th ed., 1895, p. 554.

[748] Wilder, F. A., Some conclusions in regard to the origin of gypsum, Bull. Geol. Soc. Am., vol. 32, 1921, p. 390.

[749] Cameron, F. K., Potash from kelps, Rept. No. 100, U. S. Dept. Agric., 1915; Bard, J. S., The economic value of Pacific Coast kelps, Bull. 249, Exper. Station, Coll. Agric. California, 1915; Grabau, A. W., Principles of salt deposition, 1920, pp. 91–105, 247–258.

canes may contain 13 per cent potash, and yellow banana stalks 49.40 per cent.[750]

On the Spanish coast lives a plant known as *Salsola kali* L. whose ash is high in soda, and plants of the same characteristics occur along beaches of the Canary Islands, the Argentine salt steppes, and many other parts of the world. The ash of the Spanish plants carries 14 to 20 per cent sodium carbonate.

Some plants secrete sodium chloride, such occurring in parts of Africa, where the plants are burned and the ash leached for the salt content.

It is improbable that these plants would give rise to deposits of any of the substances which they secrete, but they do place these substances in a state of concentration which might aid in forming a deposit, as is thought

TABLE 77

	MACROCYSTIS PYRIFERA	ALARIA FISTULOSA	NEREOCYSTIS LUETKEANA
Average of number of analyses	58.	15.	51.
Ash	5.90	7.50	4.20
Total soluble salts	30.00	24.40	46.90
K_2O	12.59	9.10	20.10
I	1.57	Trace	0.13
N		2.60	1.90
Range K_2O, per cent		2.90–13.10	6.58–31.62
Range N, per cent		2.10– 3.30	0.81– 3.06

to be the case for the potash in Nebraska lakes, which has been assigned primarily to leaching of ash produced by burning of dry vegetation in the surrounding region.[751]

SUMMARY

It has been shown that there are several environmental conditions permitting the formation of saline residues, but that most of them permit the formation of deposits of limited extent, purity, and thickness. Such are the salt deposits of springs, surface efflorescences, salt lakes, marginal salt pans, marine salinas, lagoons, and replacement of limestone. Deposits of each of these origins probably occur in the geologic column. The large

[750] Jenkins, E. H., Bull. 198, Connecticut Agric. Exper. Station, 1917, p. 47; Bateman, E., Chemical and metallurgical engineering, 1919, p. 616.

[751] Hicks, W. B., Potash resources of Nebraska, Bull. 715, U. S. Geol. Surv., 1921, pp. 137–138.

and thick deposits of salt and gypsum are thought to be best explained as due to arms of a sea or the ocean which retain restricted connections with the parent body for a long period of time and ultimately become a relic sea. The evaporites successive to calcium sulphate are determined by the character of the salts in solution in the beginning, by introduction of fresh water and new salts, by temperature, and other factors. After burial, there will probably be reorganization of the salts deposited and formation of new salts adapted to the pressures and temperatures of the depths of burial.

With such a variety of environments producing saline residues, it is obvious that each salt deposit constitutes a separate problem. Hence, careful studies of the salt and associated strata are essential for the solution of the origin of each salt deposit, and the environment of origin can not be determined until the stratigraphy and sediments are worked out in detail.

Sedimentary Products Dominantly Composed of Silica

The importance of silica in the formation of sedimentary rocks is strikingly obvious when it is recalled that the silica annually carried in "solution" to the sea by stream waters (319,170,000 metric tons) ranks second in quantitative importance to calcium carbonate (557,670,000 metric tons).[752] This silica is not accumulated in sea water, for analyses show mere traces. Silica-using organisms account for a small quantity, but where the remainder is precipitated, and how, have not yet been positively determined.

Sedimentary products[753] dominantly composed of silica are the radiolarian and diatom oozes, siliceous sponge deposits, siliceous sinters and other spring deposits of silica, and flint and chert. The oozes are largely composed of organic remains, and such is the case for deposits of which spicules of siliceous sponges are the dominant constituents. Sinters and other siliceous spring deposits result from evaporation, work of organisms, or changes in the condition of waters. The flints and cherts are water deposits, but the exact nature of the processes leading to their development has not yet been established.

SOURCES AND TRANSPORTATION OF SILICA

Silica is carried from the land to the places of deposition by atmosphere and water, the transportation being effected by all methods possible in these media. As transportation by traction and visible suspension results largely

[752] Clarke, F. W., Data of geochemistry, Bull 770, U. S. Geol. Surv., 1924, p. 138.

[753] In this consideration such sedimentary materials as sands and gravels are not included, although sands are largely silica and so are many gravels. These have been adequately considered in another connection.

in coarse and fine grained clastics, these are not considered in this connection. The silica transported in other forms is finely divided and colloidal and possibly in solution, although it seems probable that most of the silica stated by analyses to be in solution in stream waters is in the colloidal state[754] and not in true solution. Alkaline waters are more potent in removing silica from the original rocks than are those of other character, and Lovering found that magnesium bicarbonate and calcium bicarbonate are two of the best solvents of silica in nature.[755] Dienert[756] has stated that silica is carried in solution as alkaline silicate, and with this view Moore and Maynard are in agreement.[757] Studies by Wallace, Baker, and Ward[758] have shown that the "dissolved" silica in the waters of the Red River of the North "is colloidal to the extent that one sixth of the silica content can be separated by a centrifuge running at 40,000 revolutions per minute." Kahlenberg and Lincoln state that sodium silicate is completely hydrolyzed into colloidal silica and sodium hydroxide at a dilution of 1257 parts per million.[759] Bogue[760] found, however, that complete hydrolysis required much lower dilutions than those indicated by Kahlenberg and Lincoln. Moore and Maynard[761] conclude "that silica in solution in natural waters is transported as a true colloid provided the concentration does not exceed 25 parts per million, but if the concentration is higher it is possible for a part to be transported as alkaline silicate. The average silica content of the rivers and lakes of the world does not exceed 15 parts per million," so that essentially all of the silica in natural waters may be considered to be in the colloidal state.

Some silica may be contributed to the sea by lavas erupted on its floor or intruded into the sediments which form its floor, or by hot springs on the sea floor which are fed by magmatic waters. Appeal has been made to this source to explain the cherts of the Lake Superior iron formations,[762] the Lower Paleozoic cherts of Notre Dame Bay, Newfoundland,[763] the Devonian

[754] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 195.

[755] Lovering, T. S., The leaching of iron protores: solution and precipitation of silica in cold water, Econ. Geol., vol. 18, 1923, pp. 523–540.

[756] Dienert, M. F., Bull. Soc. Chem., vol. 13, 1913, pp. 381–394.

[757] Moore, E. S., and Maynard, J. E., Solution, transportation, and precipitation of iron and silica, Econ. Geol., vol. 24, 1929, p. 390.

[758] Wallace, R. C., Baker, W. F., and Ward, G., The Red River as an erosive agent, Proc. Trans. Roy. Soc. Canada, Sec. 4, 1926, p. 166.

[759] Kahlenberg, L., and Lincoln, A. T., Jour. Phys. Chem., vol. 2, 1898, p. 90.

[760] Bogue, R. H., Jour. Amer. Chem. Soc., vol. 42, 1920, p. 2575.

[761] Moore, E. S., and Maynard, J. E., op. cit., pp. 302–303.

[762] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior Region, Mon. 52, U. S. Geol. Surv., 1911, pp. 506–516.

[763] Sampson, E., The ferruginous chert formations of Notre Dame Bay, Newfoundland, Jour. Geol., vol. 31, 1923, pp. 571–598.

cherts of Cornwall, England,[764] the Franciscan cherts of California,[765] and cherts found elsewhere.

Table 78 shows analyses of waters carrying notable quantities of "dissolved" silica. From this table, it is apparent that the volcanic waters of the Iceland geyser are extremely high in silica both in relation to other

TABLE 78

Analyses of Natural Waters Containing Notable Quantities of Silica

	A	B	C	D	E
Cl	1.27	13.52	6.34	2.31	6.94
Br, I	Trace				
SO_4	3.93	9.01	4.90	18.74	2.26
S		0.32			
CO_3	41.47	10.16	24.93	31.43	24.15
NO_3	0.23		0.43	0.99	
PO_4	0.03				
BO_2	0.64				
Na	2.38	19.71	10.09	8.93 (Na, K)	4.24
K	0.80	1.88	1.87		4.76
Li	Trace				
NH_4	0.03	0.28			
Ca	23.54		8.50	15.44	14.69
Mg	2.56	0.08	2.59	7.50	1.40
Mn	0.17				
BaSr	Trace				
FeAl	0.10		Fe_2O_3 2.88	0.33 $\begin{cases} Fe_2O_3 \\ Al_2O_3 \end{cases}$	12.97
SiO_2	22.85	45.04	37.47	14.33	28.59
	100.00	100.00	100.00	100.00	100.00
Salinity permille	19.7	113.1	7.3	9.8	3.7

A. Big Iron Spring, Arkansas, Clarke, 196.
B. Great Geyser, Iceland, Clarke, 197.
C. Neuse River at Raleigh, North Carolina, composite of 20 samples, Clarke, 77.
D. Wisconsin River at Portage, Wisconsin, mean of 24 analyses, Clarke, 81.
E. Amazon River at Obidas, Clarke, 95.

substances and in quantity actually present, and quantitatively this figure does not seem to be exceeded by that of any river. The percentage range of

[764] Dewey, H., and Flett, J. S., On some British pillow lavas and the rocks associated with them, Geol. Mag., vol. 48, 1911, p. 202.

[765] Lawson, A. C., Sketch of the geology of the San Francisco Peninsula, 15th Ann. Rept. U. S. Geol. Surv., 1895, pp. 419–426; Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. California Publ. Geol., vol. 11, no. 3, 1918, pp. 235–432.

silica of total solids in "solution" for stream waters of North America is from 0.82 per cent in the Genesee at Rochester, New York, to 39.70 per cent in the Okmulgee near Macon, Georgia. The average for North America is 8.60 per cent. The range for South America is from 3.24 per cent in the Colorado River of Argentina to 46.22 per cent in the Uruguay at Salto, and the average is 18.88 per cent. The European range is from 0.15 per cent in the Rhine at Cologne to 32.54 per cent in the Ilz, and the average is 8.70 per cent. The average for Asia is 9.51 per cent and for Africa 17.89 per cent. The high averages for tropical countries are noteworthy and may have some significance.[766] Studies of river waters have shown that rivers high in silica are also high in organic matter; as shown later, this seems to be caused by the organic matter serving as a stabilizer to prevent the silica from being precipitated.

The average per cent of silica of the solid matter in "solution" is 11.67, which for the world indicates that annually 319,170,000 metric tons of silica are carried to the sea by streams.[766] Some is also blown there by the winds, and there are additional contributions from volcanic activity. Ocean water contains mere traces of silica. Evidently the silica contributed by streams is precipitated almost immediately on arriving at the sea, where it becomes mingled with sediments of all kinds, thus entering into shales, limestones, etc. Sediments in process of deposition whose positions are not such as to receive direct contributions from land waters should be low in silica. References will be made to this generalization on later pages.

SILICEOUS DEPOSITS MADE BY SPONGES

Spicules of siliceous sponges are rather commonly distributed in deep-sea deposits, those of the Hexactinellid sponges prevailing in the sediments of deeper waters and Tetractinellid and Monactinellid spicules in those of shallower depths. Locally sponges may be so abundant that deposits are formed of which their spicules are the most important constituents. This, however, appears to be the case only over small parts of the bottom, and their contributions to most marine sediments are of the order of magnitude of 2 to 3 per cent or less. The spicules are composed of hydrous silica and organic matter and yield on analyses a content of water ranging from 7 to 13 per cent. The evidence indicates that many of the spicules pass into "solution" not long after the deaths of their builders.

Siliceous spicules of sponges have extensive distribution in the geologic column. They occur mostly isolated and appear to be most common in chert and flint—this possibly a matter of preservation—but rarely do they

[766] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 11, 119, 139.

appear to constitute more than a minor part. They have been considered one of the sources for the silica of the cherts and flints.

GEYSERITE AND SILICEOUS SINTER

Geyserite and siliceous sinter are usually associated with hot springs. The silica deposits of springs yielding waters of surface temperatures are essentially insignificant, the silica usually occurring merely as an impurity in other materials. About many hot springs with alkaline waters the deposits are of considerable importance. The silica is a variety of opal which in geyserite has a water content ranging from 9 to 13 per cent. There seem

TABLE 79

	1	2	3	4
SiO_2	93.60	72.25	88.26	49.83
Al_2O_3	1.06	10.96	0.69	4.74
Fe_2O_3	Trace	0.76	3.26	18.00
FeO		0.31		
CaO	0.50	0.74	0.29	
MgO	Trace	0.10	Trace	
K_2O		1.66	0.11	
Na_2O		3.55	0.11	
NaCl		0.36		
H_2O	4.71	9.02	4.79	10.62
C		0.20		
SO_3		0.45	2.49	
As_2O_5				17.37
	99.87	100.36	100.00	100.56

1. Opal deposit, Norris Basin, Yellowstone National Park.
2. Geyserite incrustation, Giant Group, Upper Basin, Yellowstone National Park
3. Deposit from Scribla Spring, Icelandic geysers.
4. Deposit from Constant geyser, Yellowstone National Park, containing scoradite ($FeAsO_4 \cdot 2H_2O$).

to be few distinctions between sinter and geyserite; the latter is said to be more porous, to be frequently fibrous, and to contain more water. According to Weed,[767] spring deposits of silica result from relief of pressure, cooling, chemical reactions, evaporation, and the work of algæ. Algæ precipitate the silica upon themselves in gelatinous form, commonly brilliantly colored—golden-yellow, red, pink, and other shades. The color varies with the temperature, being white in the hottest waters and greenish in the cooler

[767] Weed, W. H., 9th Ann. Rept., U. S. Geol. Surv., 1889, pp. 613–676: Am. Jour. Sci., vol. 37, 1889, p. 351.

ones. The exact processes of deposition are not fully understood. On the death of the algæ, the silica changes to a soft cheese-like texture, and the brilliant colors are lost. New silica may be deposited in the midst of this and it may harden into a solid mass, but ordinarily there is considerable porosity. Analyses of silica deposits of some springs are given in table 79.[768] These serve to show the great range in composition.

DIATOMITE AND DIATOM OOZE[769]

Diatoms live in essentially all waters. In the ocean they seem to have their greatest abundance in waters of low salinity, as those of the Antarctic and Arctic oceans, estuaries, and off the mouths of great rivers. They also occur in the fresh waters of the land. They obtain their silica from that in "solution," which in sea water is very small, averaging only one part of silica in 250,000 of water, a quantity apparently not competent to satisfy the requirements of the organism; and perhaps from siliceous matter in suspension.[770]

Diatom tests are composed of opal, of which the formula may be expressed as $SIO_2(H_2O)_x$. It is probably a hardened hydrogel consisting originally of the two phases of silica and water, the latter diffusing into the silica and forming a solid solution.[771]

Diatoms sometimes die in enormous numbers during the so-called epidemics. In the case studied on the Pacific Coast at Copalis Beach, Washington, these seem to have been induced by dilution of sea water caused by heavy rains, followed by westerly winds and clear, sunshiny weather.[772] At such times there should be rapid accumulation of diatom remains.

Diatom ooze is named after the presence of its characteristic organic constituent. Wet ooze has a yellow straw or cream color; when dried, the color has a bluish tinge from the incorporation of terrigenous matter. Material other than diatoms consists of radiolaria and foraminifera, shell fragments, and various percentages of inorganic matter. Calcium carbonate in the Challenger samples ranges from 2 per cent in a sample from 1975 fathoms to 36.34 per cent in 600 fathoms; the average is 22.96 per cent.

The mineral particles are terrigenous and volcanic, ranging from 3 per

[768] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 207–209.

[769] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, pp. 208–213, 281–283.

[770] Murray, J., and Irvine, R., On silica and the siliceous remains of organisms in modern seas, Proc. Roy. Soc. Edinburgh, vol. 18, 1891, pp. 229–250.

[771] Rogers, A. F., in Tolman, C. F., Econ. Geol., vol. 22, 1927, p. 457.

[772] Becking, L. B., Tolman, C. F., McMillan, H. C., Field, J., and Hashimoto, T., Preliminary statement regarding the diatom 'epidemics' at Copalis Beach, Washington, Econ. Geol., vol. 22, 1927, pp. 356–368.

per cent in a sample from 1950 fathoms to 25 per cent in one from 600 fathoms, with the average 15.60 per cent. As there is such a great extent of diatom deposits in polar seas, ice-transported particles of all sizes should be present.

The upper layers of diatom ooze are thin and watery, but below the surface it is dense, compact, and probably laminated.

The average mechanical composition of five samples of diatom ooze is as follows:

Pelagic foraminifera	18.21
Bottom-living foraminifera	1.60
Other calcareous organisms	3.15
Siliceous organisms	41.00
Minerals	15.60
Fine washings	20.44
	100.00

The following analysis gives the chemical composition of a diatom ooze from a depth of 1950 fathoms in the southern Indian Ocean:

SiO_2	67.92
Al_2O_3	0.55
Fe_2O_3	0.39
$CaCO_3$	19.29
$CaSO_4$	0.29
$Ca_3P_2O_8$	0.41
$MgCO_3$	1.13
Insoluble	4.72
Loss	5.30
	100.00

Diatom ooze as an extensive deposit is largely confined to a great belt in the south polar regions, mostly between the Antarctic circle and latitude 40° south, where it covers an estimated area of 10,880,000 square miles of ocean bottom. There is a small patch in the North Pacific with an estimated area of 40,000 square miles. In depth it occurs between 600 and 1975 fathoms with the average 1477 fathoms. However, there are no reasons for considering that diatom deposits may not form on bottoms of any depth not so great that the shells pass into "solution" before reaching bottom. Diatoms seem to be as abundant over shallow bottoms as deep, but their accumulations over shallow bottoms are not apparent because of the abundance of sediments or because of their dissipation by scavengers. The Copalis Beach diatom accumulations at the time of the epidemics of 1925 extended along the beach as a continuous ridge for 20 miles and had thick-

ness from 4 to 6 inches,[773] and every fact indicates that the diatom deposits of the Upper Cretaceous and Tertiary of the Pacific Coast were accumulated in shallow water.[774] Extensive deposits have been made in fresh water.

Diatomaceous deposits of the geologic column are commonly known as diatomaceous earths. The term "earth" is, however, rarely applicable, as the materials are usually consolidated, and the most extensive deposits are firm and hard and often in extremely thick beds. Diatomite is a better term for those which are well consolidated, and shales, sandstones and limestones containing considerable admixtures of diatoms may be qualified by use of the adjective diatomaceous.[775]

Diatoms are known in the geologic column from the Lias of the Jurassic to the present, but important deposits are not known to have been made until the Tertiary. The Fairhaven diatomaceous earth of the Miocene of Maryland has a greenish colored member at the base which consists of more than 50 per cent diatom frustules. The rock on weathering becomes white to buff colored and has a known maximum thickness of 55 feet.[776] A similar deposit occurs near Richmond, Virginia.[777] The Miocene Monterey shale of California is in parts largely composed of the frustules of diatoms,[778] and several other Pacific Coast formations from the Upper Cretaceous to Pliocene locally and horizontally contain diatomite.[775]

RADIOLARITE AND RADIOLARIAN OOZE[779]

Radiolarian ooze is named from the fact that an important part of it is composed of the tests of radiolaria, and a non-calcareous ooze containing 20 per cent or more of the tests of this organism and siliceous organisms other than diatoms is designated radiolarian. As a distinct deposit it is confined to the deeper bottoms of the ocean, its distribution having a greater average depth than the red clay from which it differs in a much higher content of siliceous organisms, and into which it passes by gradual transitions. The ooze at the top is thin and watery; below the surface it is dense and compact. The tests, as those of diatoms, are composed of opal.

Radiolaria are widely distributed in ocean waters and are generally considered to be more abundant in waters some distance from land. It does

[773] Becking, L. B., etc., op. cit., 1927, p. 359.

[774] Tolman, C. F., Biogenesis of hydrocarbons by diatoms, Econ. Geol., vol. 22, 1927, pp. 454–474.

[775] Tolman, C. F., op. cit., 1927.

[776] Shattuck, G. B., Miocene volume, Maryland Geol. Surv., 1904, pp. lxiii–lxiv.

[777] Merrill, G. P., Ann. Rept. Smithsonian Inst. for 1899, 1901, p. 219.

[778] Arnold, R., and Anderson, R., Bull. 322, U. S. Geol. Surv., 1907, pp. 38–40.

[779] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, pp. 203–208, 283–284.

not seem that proof of this assumption has been produced, and there seem to be no good reasons why they are not as abundant in waters over shallow bottoms as over deep ones. They belong exclusively to the plankton and appear to be most abundant in tropical waters, particularly in the western and central Pacific and eastern Indian oceans. They are thought to obtain their silica from that in "solution" and perhaps from suspended matter containing silica.

The radiolarian content of oozes may range as high as 60 to 70 per cent and downward to around 10 per cent in the diatom and globigerina oozes and 2 per cent or less in marine deposits of terrigenous derivation.

Colors range from straw to red. Fragments of pumice, augite, feldspar, hornblende, magnetite, palagonite, magnetic spherules, and other minerals and rocks are commonly present. Manganese nodules occasionally are common and also shark teeth and other resistant parts of vertebrates. Fragments are mostly angular; some are more or less rounded; and the volcanic matter is in various stages of alteration. The average mechanical composition of the Challenger samples of radiolarian ooze is as follows:

Pelagic foraminifera	3.11
Bottom-living foraminifera	0.11
Other calcareous organisms	0.79
Siliceous organisms	54.44
Minerals	1.67
Fine washings	39.88
	100.00

Chemically, radiolarian oozes are composed very largely of silica. Calcium carbonate ranges from a mere trace to 20 per cent in a sample from 2550 fathoms, and the average in the Challenger samples is 4.01 per cent. Analyses of two radiolarian oozes are given in table 80.

Radiolarian ooze is confined to the Pacific and Indian oceans, with an area of about 1,161,000 square miles in the Pacific and 1,129,000 square miles in the Indian. It does not seem to have made any significant deposits in the Atlantic. The range in depth of the Challenger samples is from 2350 fathoms to 4475 fathoms, with the average 2894 fathoms, 164 fathoms deeper than the average for red clay[780] and nearly twice as deep as the average for diatom ooze. Although existing deposits of radiolarian ooze appear to be confined to deep bottoms, there seem to be no good reasons why such may not accumulate over shallow bottoms, as the tests are probably settling to such bottoms as rapidly as over deep ones, but are not apparent because of masking by other varieties of sediments.

[780] Murray, J., and Renard, A. F., Challenger Rept., Deep sea deposits, 1891, pp. 203–208, 283–284.

On cementation and consolidation, radiolarian ooze gives rise to radiolarite. This has not been commonly described from the geologic column, whether because of rareness or failure of recognition remains to be determined. A formation of radiolarite of late Devonian or Mississippian age with a thickness of 9000 feet occurs in New South Wales, Australia, in which radiolaria are present to the number of about one million to the cubic inch. These are not deep-sea sediments, as they contain abundant evidence of shallow-water deposition.[781] The Jurassic of the Austrian Alps contains a deposit of radiolarite consisting of red to green jasper-like layers alternating with dense, reddish or greenish gray layers of sandy and clayey marls, the entire deposit ranging in thickness from 10 to 25 meters, the increase in thickness being due to the non-radiolarite layers.[782] Wilckens[783] has described radiolarites from the Lower Carboniferous of the Rhine region and from Great Britain, and cherts containing radiolaria have been frequently reported, as those in the Mississippian of western England[784] and the Jurassic Franciscan series of California,[785] each seeming to have developed under

TABLE 80

	2900 FATHOMS	2750 FATHOMS
SiO_2	59.77	56.02
Al_2O_3	12.94	10.52
Fe_2O_3	14.29	14.99
MnO_2	0.57	3.23
$CaCO_3$	2.54	3.89
$CaSO_4$	0.29	0.41
$Ca_3P_2O_8$	0.65	1.39
$MgCO_3$	2.46	1.50
CaO	1.85	0.39
MgO	0.34	0.25
Loss	4.30	7.41
	100.00	100.00

[781] David, T. W. E., and Pittman, E. F., On the Paleozoic radiolarian rocks of New South Wales, Quart. Jour. Geol. Soc., vol. 55, 1899, pp. 16–37.

[782] Hahn, F., Geologie der Kammerker-Sonntagshorngruppe, Jahrb. d. k.-k. geol. Reichsanstalt, Bd. 60, 1910, pp. 389–390, 415–416.

[783] Wilckens, O., Radiolarit im Culm der Attendorn-Elsper Doppelmulde, Monatsb. Zeits. d. deutsch. Gesell., 1908, pp. 354–356.

[784] Dixon, E. E. L., and Vaughan, A., The Carboniferous succession, in Gower, etc., Quart. Jour. Geol. Soc., vol. 67, 1911, pp. 477–571 (519–531).

[785] Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. California Publ. Geol., vol. 11, No. 3, 1918, pp. 235–432. The Berkeley Hills, a detail of Coast Range Geology. Dept. Geol. Bull. 2, pp. 349–450.

shallow water conditions although a deep sea origin has by some been postulated.

CHERT AND FLINT

BY W. A. TARR AND W. H. TWENHOFEL

Chert and flint have a wide distribution in the geologic column. They have been studied for many years, but it is probable that less is known of the methods of their formation than of those of any other kind of common sedimentary rock. They were thought to be of igneous origin by Hutton; of organic origin by most students in the last half of the nineteenth century;

TABLE 81

	A	B	C
	per cent	*per cent*	*per cent*
SiO_2	98.17	99.47	95.50
Al_2O_3, Fe_2O_3	0.83	0.29	2.05
FeO			0.15
CaO	0.05	0.09	0.49
MgO	0.01	0.05	
K_2O		0.07	
Na_2O		0.15	Trace
Ignition	0.78	0.12	1.43
	99.84	100.24	99.62

A. Chert, Belleville, Missouri, analysis by Schneider, A. E., Bull. 228, U. S. Geol. Surv.

B. Novaculite, Rockport, Arkansas, analysis by Brackett, R. N., Rept. Arkansas Geol. Surv., vol. 4, 1890, p. 167.

C. Chert, Upper Carboniferous of Ireland, analysis by Hardman, E. T., Sci. Trans. Roy. Dublin Soc., vol. 1, 1878, p. 85.

and, during the last one or two decades, the increasing tendency has been to ascribe their formation to chemical processes.

In the strict sense, *chert* includes those crypto-crystalline varieties of quartz which are white, gray, or other light colors. *Flint* includes the dark gray and black varieties of the same material. *Jasper* is a variety colored red by iron oxide.[786] *Novaculite* is a type of chert. Early investigators had variously interpreted it as a fine-grained sandstone or as a replacement of limestone or dolomite by silica, but the most recent study by Miser and

[786] Lees, C. M., The chert beds of Palestine, Proc. Geologists' Assoc., vol. 39, 1928, pp. 445–462 (447). States that chert has a splintery fracture and flint a conchoidal fracture, probably a local distinction.

Purdue[787] has shown that it is a chert. Some novaculite contains detrital grains of quartz, however. *Jasperoid* is a common name for a chert-like rock occurring in southwestern Missouri, and adjacent parts of the bordering states, in association with the zinc and lead ores. It is stated to be somewhat more coarse-grained than average chert.[788] *Jaspilite* is a form of metamorphic chert occurring in association with the Lake Superior iron formations.

Chert and flint are dominantly composed of silica. The common impurities are small quantities of Al_2O_3, Fe_2O_3, $CaCO_3$, $MgCO_3$, FeS_2, and carbonaceous material. The chemical composition of several representative cherts is given in table 81.

Some cherts carry considerable quantities of calcium carbonate, and some pass gradually into limestone. Cherts from Kentucky have been shown to carry up to 3.5 per cent P_2O_5,[789] and many cherts contain considerable amounts of pyrite or marcasite.

The coloring matter of flint and chert may be uniformly distributed, or it may be aggregated into irregular patches, giving a mottled appearance. The mottling may take any conceivable form and distribution. The coloring matter is commonly due to included organic matter, iron oxide, minute grains of disseminated pyrite, or, indirectly, to differences in porosity of the rock. Chert and flint may be concentrically or horizontally banded. In some, the banding occurs in small irregular patches, the banded areas lying at all angles to each other and being separated by sharp lines. Concentrically banded flints and cherts are apt to have the inner bands of a darker color than those of the exterior. As a rule, the banding appears to be wider laterally than above or below, and commonly wider above than below. There is great variation in the width of the bands, some being paper-thin, and others an inch or more wide. In most materials, the banding is due to differences in composition, but in some it arises from differences in texture and porosity. Color is usually more uniform in flint than in chert.

Typical chert and flint have dense textures, and vitreous to waxy lusters, but some are more or less granular with a dull luster. Those with vitreous to waxy lusters have a conchoidal fracture and the hardness of quartz. Granular varieties break irregularly.

To the unaided eye, cherts and flints seem to be uniform in composition

[787] Miser, H. D., and Purdue, A. H., The geology of the DeQueen and Caddo Gap Quads., Arkansas, Bull. 808, U. S. Geol. Surv., 1929, pp. 49–50. This reference includes a summary of the previous views and a good bibliography.

[788] Cox, G. H., Dean, R. S., and Gottschalk, V. H., Bull. 2, Univ. Missouri School of Mines and Metallurgy, vol. 3, 1916, p. 10.

[789] Kastle, J. H., Fraser, J. C. W., and Sullivan, G., Am. Chem. Soc., Vol. 20, 1898, p. 153.

and amorphous in character, but under a high-power microscope most flints and cherts, particularly those earlier than Tertiary in age, become fine mosaics of chalcedony and quartz, together with a few particles of clay, pyrite, hematite, limonite, calcite, dolomite, and carbonaceous matter. Opaline or amorphous silica is wanting or extremely rare in Mesozoic and older flints and cherts, but may be found in those of the Tertiary and later. Calcite, or silicified, fossils in perfect forms and in fragments are commonly present. The silica that has replaced the calcite of fossils is in the form of crystalline quartz of which the grains are characteristically larger than those of the chert. Minute circular areas of quartz and chalcedony are found in some cherts. Those of Notre Dame Bay,[790] Newfoundland, show globular masses which are microscopically banded with transparent silica and silica with hematite, suggesting that the banding arose through diffusion while the material of the globule was in the form of a colloid gel. The jasperoid of southwestern Missouri is composed "chiefly of a fine-grained xenomorphic aggregate of irregular, rounded, or wedge-shaped quartz grains, the diameters of which are usually 0.02 to 0.06 mm."[791] The flint of the chalk in England is an extremely fine-grained mosaic of chalcedony and quartz.[792] The cherts which are largely responsible for the Flint Hills of Kansas are also composed of a mosaic of tiny grains of chalcedony and quartz with some calcite and limonite. Amorphous silica does not appear to be present. Weathered chert consists mainly of chalcedony.

Chert and flint may or may not contain fossils, but, if present, they are similar to those of the strata in which the chert and flint developed. The fossils may occur throughout the material or be confined largely to the outer portions. They may be calcareous or siliceous, or partly both. The preservation of these fossils is commonly excellent, usually much better than that of the fossils in the enclosing rock, particularly if the rock is a dolomite.

Form and Mode of Occurrence of Chert and Flint

Chert and flint occur in the form of globular, ellipsoidal, discoidal, and irregularly shaped nodules or concretions; as lenses; beds; cavity fillings; and cement for other types of sediments. Nodules are rather generally confined to calcareous rocks.

Nodules usually have irregular shapes, and their surfaces are commonly mammillary. Their usual position is along, or parallel to, bedding planes. They may unite with each other along the plane, and nodules of one plane

[790] Sampson, E., The ferruginous chert formations of Notre Dame Bay, Newfoundland, Jour. Geol., vol. 31, 1923, pp. 571–598.

[791] Cox, Dean, and Gottschalk, op. cit., p. 12.

[792] Tarr, W. A., The origin of chert and flint, Univ. of Missouri Studies, vol. 1, 1926 pp. 8–10.

may connect with those of adjacent planes. Some nodules are isolated and irregularly distributed within beds, and these may unite with each other to form a somewhat labyrinthine and intricate network. In some occurrences, as those in the older Paleozoic of Missouri[793] and the Pennsylvanian of Kansas, the nodules within beds are so abundant and have become so united as to constitute most of the beds. Some nodules attain a length of 10 or 12 feet and a thickness of 2 to 4 feet. Small nodules (a foot or less in length) are most common. Lenticular nodules usually have their longer axes parallel to bedding planes. Nodules of irregular shapes very commonly have the longest axis at some angle to the bedding planes, and it may be perpendicular thereto. It seems probable, however, that the most common occurrence of nodules is along bedding planes, although the planes are not always evident. Nodules may contain more or less limestone as irregular patches, some of which are connected with the surrounding limestone. They commonly contain geodal cavities lined with crystals of quartz and more rarely those of other minerals.

There is usually a sharp contact between the nodule and the enclosing rock, shown best after weathering, but in some there is no definite boundary. The outer portion of a nodule may be more or less weathered, resulting in an increase in porosity in that portion and a bleaching in color. Not uncommonly, this weathered outer portion has a chalk-like aspect.

In some formations (Burlington limestone and lower formations of Missouri and perhaps elsewhere), chert nodules occur with cracks filled with veinlets of the surrounding limestone, showing that the nodules were solid enough to maintain a crack before the enclosing limestone was entirely hardened (Tarr).

Bedded and laminated cherts are widely distributed in the geologic column; four of the most notable American examples are the radiolarian cherts of the Franciscan group of California, the Lower Paleozoic cherts of Newfoundland,[794] the jaspilite and similar rocks of the Lake Superior region, and the Rex chert of Idaho.[795] The massive chert formation of North Flintshire, Wales,[796] is also an example of this type. The beds of these cherts range in thickness from less than an inch to 1 or 2 feet. The thickness of individual beds is commonly very uniform, and the beds are very persistent. Other formations contain chert or flint in thick beds, which, however, as

[793] Purdue, A. H. and Miser, H. D., Folio 202, U. S. Geol. Surv., 1916.

[794] Sampson, E., The ferruginous chert formations of Notre Dame Bay, Newfoundland, Jour. Geol., vol. 31, 1923, pp. 571–598.

[795] Mansfield, G. R., Prof. Paper 152, U. S. Geol. Surv., 1927, pp. 367–372; Econ. Geol., vol. 26, 1931, pp. 353–374.

[796] Sargent, H. C., The massive chert formation of North Flintshire, Geol. Mag., vol. 60, 1923, pp. 168–183.

individual units are not extensively persistent. Such are the chert beds of the Pennsylvanian-Permian formations, which are responsible for the Flint Hills of Kansas.

The chert of any horizon is usually distinct from that of adjacent horizons, both with respect to characteristics and separation, the chert of each horizon having the aspect of having been formed independently of that of the adjacent horizons. Within each horizon, the chert may have a wide distribution, with but slight variation in character. This is illustrated by the cherts of the Oneota dolomite of the upper Mississippi Valley; those of the Pennsylvanian limestone members of Kansas and Oklahoma; and the Carboniferous cherts of Ireland, England, Belgium, and elsewhere.

Chert and flint have been found on the interior of fossils. This introduction is supposed by some to have been by ground water, but may be more accurately explained as a filling of the fossil by the original silica while yet soft. Chert and flint also serve as cement for various clastic sediments, as illustrated by the French Cretaceous formation known as "gaize."[797] A conglomerate at the base of the Trinity formation of Texas is locally similarly cemented by "amorphous" silica. In the Lower Paleozoic of Notre Dame Bay, Newfoundland, the spaces between pillow lavas are filled with chert.[798] The jasperoid in the Tri-State area cements the original broken chert.

The Rocks Associated with Chert and Flint

Nodular chert and flint occur almost wholly in association with calcareous strata. The nodules in chalk are very commonly flint; those in dolomites and limestones are commonly chert. However, chert nodules occur in chalk and those of flint in limestone and dolomite. Bedded cherts and flints are in association with shales, limestone, and sandstone. Vein flints and cherts occur (such occurrences are rare) in any variety of rock.

Geologic Distribution

Chert and flint are probably present in the calcareous strata of every geologic period. Chert interbedded with other types of sediments occurs in the Pre-Cambrian formations of the Lake Superior and Hudson Bay regions and in Wyoming; the Ordovician of southern Scotland; the Lower Paleozoic of Newfoundland; the Devonian of Cornwall and eastern Australia; and the Franciscan of California. Cherts in limestones and dolomites are abundant in the Upper Cambrian of the Appalachian region, the Mississippi Valley, and the western part of the United States; the Ordovician Knox dolomite and Shenandoah limestone of the Appalachians, some of the

[797] Cayeux, L., Mém. Soc. Géol. du Nord, vol. 4, pt. ii, 1897.
[798] Sampson, E., op. cit., p. 577.

Ordovician limestones of the Mississippi Valley, Texas, New Mexico, and Arizona; the Niagara limestone of the upper Mississippi Valley and the Great Lakes region; the Lower Devonian of the Appalachians and the Mississippi Valley; the Mississippian of the Mississippi Valley and Europe; the Pennsylvanian of the Mississippi Valley and parts of the Rocky Mountains; and the Cretaceous of both Europe and America. Chert is so abundant in parts of the Pennsylvanian strata of Kansas as to cause an important physiographic feature, the Flint Hills, before mentioned.

A fact of interest in connection with the distribution of the nodular cherts is that the equivalents of containing strata in some other parts of the world do not carry chert. Thus, the Beekmantown and Chazy limestones and dolomites of the Mingan Islands and Newfoundland have little chert, although their equivalents in the Mississippi Valley are filled with it. The Silurian rocks of Gotland and Anticosti carry no cherts, but those of the Great Lakes region and upper Mississippi Valley have it in abundance. This distribution must be related to the paleogeography of the times; the depths of water; and the nature of the water bodies and their relations to the open sea, the land, and the streams draining therefrom. Bedded cherts may be associated with pillow and ellipsoidal lavas, and this association probably has some bearing on the origin of the siliceous sediments.

Origin and Time of Development of Chert and Flint

The theories relating to the origin of chert and flint must be concerned with the source of the silica; the processes and agents responsible for its concentration and precipitation; the environment in which deposition occurred; and the time relationships to the enclosing rock. There is wide diversity in the evaluation of these various elements by different students of the subject, one emphasizing one set of factors in the process and another emphasizing a different group. The factor which has been considered the least and yet which is of as much if not more significance than the others is the source of the silica. Especially is this factor of necessary consideration by those advocating a secondary origin of chert and flint.

Source of the Silica. The quantity of silica in the form of chert and flint occurring in sedimentary rocks is enormous. The amount can scarcely be estimated in such formations as the Rex chert, with a thickness of 60 to 110 feet over hundreds of square miles; the Lower Paleozoic formations of the Mississippi Valley; the Knox dolomite, a formation 3,500 to 4,000 feet thick and estimated to contain a total of 800 to 1,000 feet of chert; and the chalk of England and France. In explaining the origin of these formations, it is as essential to have an adequate source for this silica as it is to have a source for the material in the enclosing beds. The literature contains little

information as to the source of the silica of chert and flint, the authors having apparently assumed that if silica was present it was derived just as were the materials of the enclosing limestone or other sedimentary rock. However safe this assumption may be for those students who advocate the chemical deposition of chert and flint directly on the sea floor, the supporter of a secondary origin is required to shift these enormous quantities of silica about in solid rock, and for him an adequate source of such amounts of silica is a real problem. The source of the silica should not be ignored, however, under any theory.

Davis[799] in his discussion of the radiolarian cherts of the Franciscan group in California discussed the source of the silica and ascribed it either to the lavas associated with the cherts or to reactions, due to the lavas, that formed silicates which altered to chert. Others have sought to explain the silica as having been derived from igneous rocks or magmas below the sea. Siliceous springs have been suggested as a source. Those believing in an organic source for the silica think that organisms secured it from the sea water, which had received it from the land or through the decomposition of silicates in the sea. That chert and flint do not occur more commonly is due to the fact that when muds were carried to the sea most of the (colloidal) silica was deposited with them, as is being done at present. The view that the silica was derived from the land during the process of weathering thus ascribes the same source to the silica as is accepted for the calcium carbonate in limestone and dolomite. The detailed chemical studies of Moore and Maynard (which will be described) give further support to this view of the source of the silica.

Aside from possible igneous sources in the sea, the logical source is the land. Clarke's[800] averages of the composition (believed to be more accurate than those of Sir John Murray) of the river waters of the world have revealed that the second most abundant material annually added in solution to the sea by rivers is silica. Silica furnishes 11.67 per cent and calcium 20.37 per cent of these materials added to the sea. This amounts to 319,170,000 metric tons for silica and 557,670,000 metric tons for calcium. As there is essentially no silica in the sea water, this silica is deposited in some form. Tarr[801] pointed out that during a period of peneplanation when chemical denudation would be at a maximum much greater quantities of silica would be carried to the sea. During such a period of low-lying lands, the seaward movement of clastic materials would be restricted and the forma-

[799] Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. of California Publ. Geol., vol. 11, 1918, pp. 235–432.

[800] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 119.

[801] Tarr, W. A., Origin of the chert in the Burlington, Am. Jour. Sci., vol. 44, 1917, pp. 409–452.

tion of carbonate rocks favored. Thus, the formation of limestone and of chert would be favored at the same time, which explains the common association of the two rocks. A study by Tarr of the paleogeography of the Paleozoic and Mesozoic periods supported this view that low-lying lands were associated with the abundant deposition of chert and limestone.

Causes of Precipitation of Silica. Essentially all silica is transported as a colloid. That transported as the aluminous silicate (clay) does not enter into our discussion. The clay is of significance in our present problem only if present in large quantities (as in muddy waters entering the ocean), whereupon the colloidal silica having been coagulated by the electrolytes of the sea water goes down with the clay. An unsettled question regarding the colloidal silica is whether it is transported as sodium silicate (the composition of common water glass). The general view held by chemists and most students of ground waters and streams is that the colloidal silica is not so transported, but also that it is probably not one of the specific silicic acids such as H_4SiO_4 or H_2SiO_3. It is much more probable that the colloidal silica in solution is far more dilute than these; for example, one part of SiO_2 to hundreds or even thousands of parts of water. A silicic acid gel containing one mol of silica to 300 mols of water is solid enough to be broken apart, but will coalesce again by flowing together. As further evidence concerning the character of colloidal silica, it may be noted that quartz can be ground extremely fine and then converted into colloidal silicic acid by boiling in hot water. The process of weathering favors the formation of the colloidal silica, as the alkalies unite much more readily with the carbonate, sulphate, or chloride acid radicals present in the ground water.

The colloidal silica particle has a sheath of water molecules about it, which favors its stability. Most of the colloidal silica transported by ground water in streams is a hydrophilic colloid and not very sensitive to electrolytes. Hydrophilic colloids adsorb much water (a fact in keeping with the large amount of water in a hydrosol solution), and it is this marked hydration that is an important factor in the stability of such sols.[802] A sol may be further stabilized by adsorbing an ion with its electric charge, thereby making it necessary to have a larger amount of the oppositely charged ion to neutralize it and so bring about coagulation. Another factor in the stabilization of a colloid is the presence of a so-called "protective colloid." Organic colloids are especially good as protective colloids. Authorities are not agreed as to whether this protective colloid forms a film about the other, or whether they adsorb each other. As some of these factors of stabilization are difficult to determine, it is not surprising that variable results are secured when silica sols are experimentally coagulated.

[802] Freundlich, H., Elements of colloidal chemistry, 1924, p. 149.

The coagulation of a sol may be accomplished by decreasing the hydration or, as is more common, by neutralizing the charge on the colloidal particles through the addition of electrolytes of the opposite charge (for a silica sol, this is usually a positive charge) to the solution. After neutralization, the coalescence of the particles follows, more or less rapidly, as a result of their colliding, and thus depends on their concentration and velocity. There is a wide variation in the neutralizing ability of univalent, bivalent, and trivalent ions. Ordinarily, ions of the higher valency are adsorbed more readily and are more effective in coagulating the particles; but the concentration, character of the charge, and rate at which the electrolyte is added influence the coagulating power of the ions and may even reverse the process.[803]

This discussion of sols in general, with some reference to the character of silica sols, will enable us to understand better the experimental data given below. Much more work on sols (especially silica sols) is needed, with known degrees of hydration and known adsorption of ions and influence of protective colloids.

Several workers have experimented with the precipitation of colloidal silica, but without concordant results. Their work, however, contributes much of value to the study of chert and flint. Tarr[804] conducted a short series of experiments, using artificial solutions of $NaCl$, $MgSO_4$, and K_2SO_4 in the proportions in which they occur in sea water, and the $NaCl$ and $MgSO_4$ separately. His sodium silicate solutions consisted of 27.07 parts of silica per million, and half, and twice that quantity. He obtained a heavy precipitate of gelatinous silica in each test, and therefore concluded that colloidal silica is coagulated through the neutralization of the negative charges on the colloidal silica particles by the positively charged ions of sodium, potassium, calcium, and magnesium.

Lovering's[805] experiments carried the work still further. He used natural sea water and obtained results not in agreement with Tarr's in that there was no precipitate with sodium silicate solutions containing 30 parts of silica per million (possibly due to the stabilizing effect of the organic matter in the natural sea water). He obtained precipitation, however, from sodium silicate solutions containing 490, 6,000, and 8,000 parts of silica per million. Lovering concluded that 1 cc. of sea water will precipitate 0.0155 grams of silica from a sodium silicate solution, providing the concentration is sufficiently high, that precipitation is never complete, and that none occurs in

[803] Bancroft, W. D., Applied colloid chemistry, 1921, pp. 212–259.

[804] Tarr, W. A., Origin of the chert in the Burlington limestone, Am. Jour. Sc., vol. 44, 1917, pp. 409–452. See also The origin of chert and flint, Univ. of Missouri Studies, vol. 1, no. 1, 1926, pp. 24–32.

[805] Lovering, T. S., The leaching of iron protores; solution and precipitation of silica in cold water, Econ. Geol., vol. 18, 1923, p. 537.

solutions containing less than 36 parts silica per million. He also concluded that 275 parts silica per million may fail of precipitation in a slightly alkaline solution in the presence of a large quantity of electrolytes.

Moore and Maynard's[806] studies are the most complete to date, however. They used three types of solutions containing silica: (1) sodium silicate, (2) dialyzed sodium silicate, and (3) sodium silicate solutions mixed with hydrochloric acid and then dialyzed. Each of the solutions, with the exception of the undialyzed sodium silicate, contained the silica in the colloidal form, and even in the sodium silicate the greater part was probably a colloid. Moore and Maynard found that precipitation was a complex process and obtained variable results where uniformity was expected. This variability, however, as pointed out above in the discussion of colloids, should be regarded as highly probable.

Moore and Maynard concluded from their experiments that calcium bicarbonate and sea salts are two of the best precipitants of colloidal silica from sodium silicate solutions, that sodium chloride and potassium sulphate are not so effective, and that time is an extremely important factor. Magnesium sulphate produced no or little precipitation in sodium silicate solutions containing 30 parts of silica per million, faint precipitation in those with 60 parts per million, and greater effects with increasing concentration in silica up to the limit of the experiments of 480 parts per million. Not all of the silica could be precipitated, the quantity remaining in solution increasing with the original concentration and ranging from 28 parts per million in the 30 parts per million silica concentrate to 104 parts per million silica in solutions containing 480 parts per million. It seems quite certain that a part of the precipitate was magnesium silicate. Sodium chloride and sea salt were the most effective precipitants of dialyzed sodium silicate solutions, and time was an important factor in precipitation though even then not all the silica was precipitated. Magnesium sulphate gave little precipitate, as did also calcium bicarbonate. A silica hydrosol prepared by dialyzing a mixture of sodium silicate and hydrochloric acid yielded after 75 days little precipitate with sea salt, sodium chloride, magnesium sulphate, magnesium bicarbonate, and calcium bicarbonate, showing that this type of silica is probably unimportant in the origin of chert and flint. The magnesium bicarbonate and calcium bicarbonate tended to dissolve more silica from the walls of the container rather than to precipitate the colloidal silica already in solution, which agreed with the findings of Lovering that these two salts in nature are not precipitants but common solvents of silica.

Considerable has been written with respect to the precipitating ability

[806] Moore, E. S., and Maynard, J. E., Solution, transportation, and precipitation of iron and silica, Econ. Geol., vol. 24, 1929, pp. 403, et al.

of calcium and magnesium bicarbonate. Church[807] states that 1 mg. of powdered calcite would convert a 1-per cent silica solution into a gel within 10 minutes time. Cox, Dean, and Gottschalk[808] obtained no results on treatment of a dialyzed mixture of water glass and hydrochloric acid with calcium carbonate, but did obtain a strong precipitate with a calcium carbonate solution saturated with carbon dioxide. Lovering,[809] on the other hand, has shown that a dilute dialyzed solution similar to that used by Dean in the presence of calcium bicarbonate retains considerable silica in solution, and he concluded that magnesium and calcium bicarbonate rarely act as precipitants of silica in nature but that calcium bicarbonate will precipitate colloidal silica when the concentration is over 40,000 parts per million, a state of concentration so rare in nature as to be of no importance. Moore and Maynard have shown these salts to be ineffective precipitants in such solutions as ordinarily occur in nature and to become important only when the concentration is high, under which conditions carbon dioxide and calcium carbonate also function. The time factor is important. They explain the disagreements of earlier results on the basis of difference in degree of concentration of the silica solution.

As previously noted, sodium chloride is a poor precipitant of colloidal silica formed from dialyzing a mixture of sodium silicate and hydrochloric acid, and also ineffective in undialyzed sodium silicate solution, whereas it acts very effectively in dialyzed sodium silicate solutions with the same concentration in silica. Calcium bicarbonate is an efficient precipitant in undialyzed hydrosols (sodium silicate), but ineffective in dialyzed hydrosols. Explanation of these facts is difficult, but Moore and Maynard suggest that in some cases the silica may be in true solution, in others have become stabilized by adsorption of various ions, and in still others that the character of the solutions and electrolytes may have reversed the charge. Hardy[810] has stated that silica is positively charged in acid solution and negatively in alkaline or very feebly acid solutions, and thus under some conditions a given electrolyte would be effective as a precipitant and in others not. The real coagulating factors are the ability of the colloidal particles to adsorb ions, and the valency of the ions adsorbed. Ions of a higher valence are, in general, more readily adsorbed; but some substances may adsorb better those having lower valencies, which was possibly a

[807] Church, A. G., Jour. Chem. Soc., vol. 15, 1862, p. 107.

[808] Cox, G. H., Dean, R. S., and Gottschalk, V. H., Studies on the origin of Missouri cherts and zinc ores, Bull. 2, Univ. Missouri, School of Mines and Metallurgy, vol. 3, 1916, pp. 5–34; Dean, R. S., The formation of Missouri chert, Am. Jour. Sci., vol. 45, 1918, pp. 411–414.

[809] Lovering, T. S., op. cit., 1923, pp. 537–538.

[810] Hardy, W. W., Chemistry of colloids and some technical applications, 1915.

factor in some of Moore and Maynard's experiments though it is also evident that other stabilizing factors were present.

Many geologic formations contain deposits of iron and silica in such relationships that there must have been more or less simultaneous precipitation of these substances. On an earlier page, it was shown that electrolytes in sea water precipitate ferric oxide almost immediately. Above, it has been shown that silica also is precipitated, but more slowly. Taken separately, the two substances were found to be quite stable in the low concentrations present in land waters. On the other hand, mixing of solutions of ferric oxide and silica led to the immediate precipitation of the iron and a part of the silica,[811] which, according to Thomas and Johnson,[812] is due to removal of peptizing agents by chemical action between the two substances, with complete precipitation taking place under certain conditions of concentration. With concentrations of 20 parts per million of ferric oxide and 60 parts per million of silica, Moore and Maynard obtained precipitation of most of the iron and about half of the silica. With conditions as they exist in natural waters, evidently other substances must be present to make ferric oxide and silica stable in the presence of each other. Clarke[813] gives some data that have a bearing upon the stabilization of these two colloids. His data regarding the composition of river waters show that organic matter in solution made possible the transmission of a much larger quantity of silica and iron. He did not recognize, however, that it was the stabilizing effect of the organic matter that held the silica and ferric oxide in solution longer. Moore and Maynard found that peat solutions acted quite effectively as stabilizers. One cubic centimeter of peat solution containing 92.2 parts of organic matter per million served to stabilize 200 cc. containing 10 parts of ferric oxide per million and 30 parts of silica per million. This organic matter after mixing with the other solutions became 4.5 parts per million of the whole, making it obvious that natural waters the concentrations of which approximate or rarely exceed the above will have no difficulty in transporting silica and ferric oxide, providing organic matter is present to the extent of 4.5 parts per million. With greater quantities of organic matter, greater stability exists. On reaching the sea, the iron is rapidly precipitated by the electrolytes in solution, whereas the silica remains a longer time in solution. The quantity of organic matter in solution in the rivers of the world averages greater than 4.5 parts per million, an amount adequate to stabilize and transport all silica and ferric oxide carried by natural waters. The precipitation of ferric oxide first and silica later gives

[811] Moore, E. S. and Maynard, J. E., op. cit., 1929, pp. 512, and references.
[812] Thomas, A. W. and Johnson, L., Jour. Amer. Chem. Soc., vol. 45, 1923, p. 2532.
[813] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, p. 110.

rise to a deposit of two bands. New inflows of silica and ferric oxide would form additional layers and thus give rise to a thinly banded siliceous and ferruginous deposit.[814]

The considerations outlined above show that after the carrying waters have come in contact with those of the sea the silica is in time precipitated, and that the delay in precipitation is due to the stabilizing effect of the organic matter, which prevents precipitation until a considerable saturation has been reached.

It should be emphasized that, in the experiments noted above, not all of the silica in a solution was precipitated; in fact, that the amount remaining greatly exceeds the amount present in the sea water of today. The longer the time of the experiment, the greater the precipitate obtained, though even so, much still remained in solution. There can be no doubt of the value of the experiments made by these men, as they point to possible and probable means of precipitation of colloidal silica. Tarr, however, has pointed out that the deposition of silica from sea water in the past and at present has been and is far more complete than the laboratory experiments show. This is shown by the scarcity of silica in the present sea water (one or two parts per million) and the surprisingly low content of silica of the carbonate rocks that enclose chert and flint. The silica content of these rocks is essentially the same as for carbonate rocks free from chert and flint. This points to a rapid and complete precipitation of all the silica of sea water once saturation is reached, and shows us that as an efficient laboratory the supposedly complex ocean still surpasses man's best efforts.

During periods of dominant limestone deposition, it is evident that rapid precipitation of silica occurred from time to time. It seems probable, moreover, that the process of inorganic deposition has remained essentially the same since rivers have been contributing silica to the sea, and that this method has accounted for most of the deposition of the silica, though some was deposited by other means and with other materials. Organisms account for a part, the amount varying with the life of the period. Radiolaria do not seem to have existed in Pre-Cambrian time, nor diatoms before the Jurassic, and it may be that there have been times when silica-secreting organisms did little work. These would have been times of greater concentration of silica in ocean waters.

Part of the precipitated silica settles to the bottom to mingle with other sediments, especially clays and silts. The deposition occurs mostly adjacent to the places of mingling of stream waters with each other, those of lakes, or those of the sea. Colloidal silica readily unites or is coagulated with

[814] Moore, E. S. and Maynard, J. E., op. cit., 1929, pp. 516–520.

muds and silts, hence during periods of mechanical erosion when these sediments were being brought in, most of the silica in the sea waters would be carried down by and deposited with these clastic materials. During times of low lands, with transportation of clay and silt (or sand) greatly reduced or entirely stopped, calcareous sediments would accumulate adjacent to the land. If the accumulation of these sediments was sufficiently slow, it would be possible for the silica to form a distinct deposit, or at any rate, at the places of its dominant precipitation to constitute a large part of the calcareous sediments deposited. As the material precipitated is a gel, under conditions of slow deposition of other sediments the small particles might aggregate and continue growth because of the attraction a large body has for small particles of the same material. Also, some silica would probably be directly acquired from the surrounding waters.

Reference was made above to a paleogeographical study of chert and flint made by one of the authors (Tarr). The maps made showed that the greatest deposition of chert and flint had occurred in those broad, shallow epicontinental seas that were likewise the sites of limestone, chalk, and dolomite deposition. Formations, such as those of the Ordovician, Devonian, Mississippian, Pennsylvanian, and Cretaceous, which are uniformly cherty or siliceous over widespread areas must have been deposited in such shallow epicontinental seas. Silica was evidently contributed to such a sea from various areas, and was then uniformly distributed throughout the sea in the same manner as was the material for the limestone or other carbonate rock being laid down. Undoubtedly, the two materials, having the same source (the land), transported in the same way (streams to the sea), were both carried far and wide to be deposited over the entire epicontinental sea floor.

It is probable that if the quantity of silica carried by any stream was great enough to be near the saturation point, or if it accumulated locally near the stream inlet, deposition might occur under localized conditions. Twenhofel regards the cherty Pennsylvanian formations of Kansas (largely marginal and containing some fresh-water deposits) as having been formed where fresh and salt waters mingled. This assumption is not applicable to the cherty limestones of the Pennsylvanian in Missouri. As Twenhofel has stated, there is no direct evidence that such localities are the seat of such deposition. The wide-spread chert-bearing horizons are more apt to have been the result of epicontinental sea conditions.

Some writers have maintained that as the process of weathering proceeds, liberated silica is carried downward and redeposited in cavities and veins, replacing fossils, or as chert and flint. Some have suggested that silicified surfaces might result from this process, but the soil scientists who have carefully analysed both soil and subsoil do not support this view. That

silica is transported by the ground water is readily shown, and no doubt the quartz crystals of geodes and the quartz (not chert) replacing fossils have been formed in this manner, but that chert and flint were formed by this method is improbable if not impossible. If this process of concentrating silica were at all common, geodes should be far more abundant than they are, as limestones, the world over, contain some siliceous material, all of which is freed when the limestone goes into solution. Yet geodes are the exceptional feature of such rocks, and when present are more commonly lined with calcite or dolomite crystals than with quartz.

Silicified fossils have long been regarded as evidence in favor of the theory that chert and flint are formed by circulating ground waters. The statement has been made that such silicified fossils are chert, but Tarr has never found such a one though for years he has been studying these features. Fossils replaced by quartz are not uncommon and such *occur in chert.* Replacement of fossils by chalcedony is possible, but those silicified fossils studied by Tarr contain little or no chalcedony. The so-called "beekite" (which is nothing but chalcedony) found on the surface of fossils is the most common occurrence of such replacement. Is it not probable that the fossils that were supposed to have been replaced by chert were actually replaced by chalcedony? This could be determined because under the microscope chalcedony shows a typical fibrous character with a dark cross between crossed nicols, which chert and flint do not.

It should be noted that silicified fossils originally presented an opening above capillary size. Many of the so-called silicified fossils are merely lined or covered with quartz crystals and not wholly replaced. A fundamental chemical reason underlies this, which will be dealt with below in discussing more fully the possibilities of weathering. A meager fauna in a limestone or dolomite formation, occurring only as silicified forms in residual chert (as in some of the Ozarkian formations), is frequently advanced by paleontologists as proof of the epigenetic origin of the chert during weathering.[815] The few fossils found in these carbonate rocks are imperfect and poorly preserved, whereas those in the chert are much better preserved. Why a few of the fossils should remain in better condition until weathering occurred no one has explained. The logical explanation of all this is that the fossils of the chert were imbedded in it and replaced by silica at the time of burial and thus before the formation was recrystallized, which process destroyed the other fossils of the rock.

Finally, the vast number of unconformities in carbonate and other rocks which have absolutely no evidence of silicification would seem to be adequate

[815] Dake, C. L., Geology of the Potosi and Edgehill Quadrangles, vol. 23 (second series), Missouri Bur. Geol. and Mines, 1930, pp. 129, 146, 166.

proof that a concentration of silica at weathered surfaces does not occur. If it did, the subsurface geologists would have made use of it in their work.

ENVIRONMENTS OF FORMATION. Where it has been possible to determine the environment of a deposit in which significant amounts of flint and chert occur, that environment has been determined as having been salt water. There is proof also that these waters were shallow and that the greatest development of chert and flint was in widespread epicontinental seas that were surrounded by low-lying lands, a condition favoring a maximum of chemical weathering. Proof of the saltiness of the waters in which such extensive deposits as those of the Lake Superior iron ores were formed is lacking, but there is no doubt that these waters were shallow and subject to land influences. Silica brought to the sea bottom from magmatic sources might give rise to chert or flint deposits at any depth and at any distance from land, and it may be that extensive deposits exist beneath the deep sea. Likewise, the organic siliceous oozes are deposited at great as well as at shallow depths, and if these can give rise to chert or flint deposits such chert or flint might thus have been formed at great depths. No chert or flint deposits of this type are known on the land, however. Twenhofel states that lake deposits of arid regions contain considerable chert or flint, which had probably been deposited in salt water through the same causes and in the same places of precipitation as were those deposits known to have been formed in the sea.

TIME RELATIONS OF CHERT AND FLINT TO THE ENCLOSING ROCK. The various suggestions relating to time relations of chert and flint to the enclosing rock may be tabulated as follows:[816]

A. Formed after the consolidation of the enclosing rock. Epigenetic origin.
B. Formed contemporaneously with the accumulation of the materials of the enclosing rock. Syngenetic origin.
C. Formed penecontemporaneously with the accumulation of the materials of the enclosing rock. Syngenetic origin.

(A) Chert and flint to be of epigenetic origin must either replace the original rock or fill cavities therein. Replacement is generally considered

[816] On the consideration of the time relationships of cherts to the enclosing rocks, consult (a) Brydone, R. M., The origin of flint, Geol. Mag., vol. 57, 1920, pp. 401–405; (b) Richardson, W. A., The relative age of concretions, Geol. Mag., vol. 58, 1921, pp. 114–124; (c) Sargent, H. C., The Lower Carboniferous cherts of Derbyshire, Geol. Mag., vol. 58, 1921, pp. 265–278; (d) Massive chert formations of North Flintshire, Geol. Mag., vol. 59, 1923, pp. 168–183; (e) Further studies in chert, Geol. Mag., vol. 66, 1929, pp. 399–413; (f) Tarr, W. A., Origin of the chert in the Burlington limestone, Am. Jour. Sci., vol. 44, 1917, pp. 409–452; (g) Twenhofel, W. H., The chert of the Wreford and Foraker limestones along the state line of Kansas and Oklahoma, Am. Jour. Sci., vol. 47, 1919, pp. 407–429. Other papers in which time relationships are considered may be found in bibliographies or footnote references of the articles noted above.

to be the more common method, and it is assumed that ground water introduces the silica in solution. Except that replacement took place after consolidation, no limits are placed upon the time relationships. Also, it may occur in rocks at the surface or at some distance beneath. Most of those holding the replacement theory have assumed that permeating ground waters carrying silica in solution have substituted it for some part of the rock entered. There are several serious objections to any general application of this theory. These are: (1) cherts do not commonly preserve original structural or textural features of the rocks assumed to have been replaced; (2) many structural and textural features end where the chert begins; (3) chert nodules are distributed with little relation to channels of underground water circulation, such as joints and bedding planes; (4) occurrence of chert nodules is common along horizontal planes which may be independent of bedding planes; (5) fossils are better preserved in chert nodules than in the enclosing rock; (6) some of the rocks associated with cherts possess relative impermeability, which would greatly curtail, if not actually prohibit the passage of silica-containing solutions through them; (7) colloidal silica is a solid particle and thus cannot migrate through a solid limestone or dolomite, and, as much chert and flint occur within a bed (as along the bedding plane), such migration would be essential if chert were epigenetic in origin; (8) no explanation of the position of a series of nodules or lenses within a massive bed is possible under the replacement theory; (9) an adequate source of the silica necessary for replacement is unknown; and (10) most carbonate rocks are impermeable by ground water save along divisional openings. Some of the facts just enumerated are also opposed to the view that very much chert and flint could result from the filling of cavities. Moreover, not much chert and flint have been found that have the forms or shapes that would result from cavity fillings.

There are two general regions in which epigenetic cherts and flints might form: (a) the zone of cementation below the water table, and (b) the zone of weathering above the water table.

(a) The formation of chert in the zone of cementation below ground-water level would be confined to divisional openings in rocks or to porous rocks such as sandstones. As noted above, there is no evidence that chert and flint are related to these openings. Neither are vein deposits of chert known. Sandstones form quartzites by being cemented with quartz and, rarely, with chalcedony which is probably then called "chert." The point is sometimes made that small calcareous areas within chert and flint represent unreplaced remnants of the surrounding rock. These areas are as readily explained as being due to the inclusion of calcareous materials in the chert during its accumulation, or as being the result of the aggregation

of both the calcium carbonate in the gel and that which had migrated into it. The migration of such salts in gels is a common phenomenon.

The evidence against replacement afforded by well logs is very positive. Studies of hundreds of thousands of well logs prove that chert and flint are as widely distributed underground as are the formations in which they occur. Denial of this is made by some who explain chert as a product of weathering, but the evidence is so overwhelming as to be incontrovertible. Lee[817] gives positive proof of this widespread occurrence of chert by his sections and statements that beds (up to 10 feet thick) and nodules of chert are abundant in the Gasconade formation throughout its occurrence. Lee tries to explain and apply Ulrich's view of the origin of the chert, but is forced to conclude that the bedded and other cherts are "apparently unassociated with any of the phenomena of unconformity or surface weathering." Geologic sections accompanying hundreds of papers and reports furnish like evidence of the widespread distribution of the chert in a formation, and thus show that the authors of the reports do not regard the chert as a product of weathering.

A further argument against replacement is that a determination of the composition of various cherty formations has shown that the silica content of the enclosing rock is very low. An extremely cherty formation in Missouri, the Eminence, is stated by Dake[818] to contain 0.22 per cent of silica in a sample taken near its base and 0.28 per cent in one taken near its top. The chalk associated with the flint in England shows a similar low silica content, and many other examples could be cited. Now, either these rocks never contained silica or it has been completely removed. Evidently, they never contained it, for, as has been pointed out above, particles of colloidal silica cannot be moved through these dense fine-grained calcareous rocks. Moreover, even if the colloidal silica could be moved through the rock, it would not be necessary to assume that it had been, as any silica scattered through the rock could just as readily be explained as having been disseminated from the chert horizons. And finally, the scarcity of silica in a limestone or dolomite associated with chert is evidence of the complete chemical precipitation of the silica at intervals of time represented by the vertical spacing of the chert and flint horizons within the rock.

The statement is frequently made that cherty horizons are associated with unconformities. If a marked connection existed between peneplanation (with the resultant greater chemical denudation in the later stages) and an abundance of limestone and chert, then chert should be more abundant in

[817] Lee, W., Geology of the Rolla Quadrangle, Missouri Bur. Geol. and Mines, vol. 12, 1913, pp. 12–19.

[818] Dake, C. L., op. cit.

the upper part of a limestone bed. A preliminary study has shown this distribution to be fairly common, but the study is not complete and a positive statement cannot be made at present. That it is commonly true is indicated by such an assumption on the part of those advocating a secondary origin for chert. It is not always true, however, and hence cannot be used to prove that chert is secondary. Many exceptions to this distribution of chert are known, of which a recent citation from Woodward, who attempts to show that certain cherts of Virginia are secondary,[819] will be made. In one formation (the Becraft) described by Woodward, the chert is in the middle; and in another (the Keyser) it is near the base and near the top. The distribution in both of these formations thus furnishes evidence against Woodward's view.

Various writers have supported the replacement theory, but none have definitely proved that replacement has occurred or met the various criticisms mentioned above. Barton,[820] Sollas,[821] Van Hise,[822] Sellards,[823] and others have advocated replacement in some degree.

(b) Surface weathering of a formation has been advocated as the means of concentrating the contained silica, which is then assumed to have been deposited in the form of chert. Silica is present to a greater or less extent in most rocks, although the quantity in carbonate rocks is generally low. On the decomposition of the containing rocks, this silica is released and most of it becomes a part of the soil and is later removed with it during soil erosion.

A small portion of the silica released during weathering, however, is removed by the ground water, either as a colloid (the usual form) or as a silicate. Spring and well waters (typical ground waters) contain very small amounts of silica (even the springs at Hot Springs, Arkansas, contain only 47 parts of silica per million). Furthermore, it must be remembered that the studies of soils and soil solutions by the soil scientists have shown that there is little or no downward movement of silica, save in the tropics where lateritic soils develop. The valuable studies of these men have been overlooked in previous discussions of the origin of chert, and there can be no doubt as to the significance of their findings in the problem; for, if there is no downward movement of the silica produced by weathering (save where

[819] Woodward, H. P., Paleozoic cherts of West-Central Virginia, Jour. Geol., vol. 31, 1931, pp. 277–287.

[820] Barton, D. C., Notes on the Mississippian chert of the St. Louis area, Jour. Geol., vol. 26, 1913, pp. 361–374.

[821] Sollas, W. J., Age of the Earth, 1912, p. 152.

[822] Van Hise, C. R., Treatise on metamorphism, Mon. 47, U. S. Geol. Surv., 1904, p. 818. See also pp. 816–820; 847–853.

[823] Sellards, E. H., 1st Ann. Rept., Geol. Surv. Florida, 1908, p. 48.

lateritic soils are developing), the commonly accepted source for the silica of secondary chert is removed. That some silica is carried in ground water is not doubted, but the quantity is wholly inadequate to account for the chert and flint in limestones and dolomites, even if there were no other objections to their formation there. The small amount of silica carried, 1 to 10 or 15 parts per million, may in time line a geode or the inner cavity in a fossil, but even this requires a vast period of time. It should be noted, moreover, that rapid precipitation of silica favors the formation of a colloidal gel that would become chert or flint; slower deposition by moderately warm or cold solutions favors the formation of chalcedony, as found in ore veins near the surface; and very slow deposition by ground water favors the formation of quartz, such as that constituting the cement in sandstone and forming geode linings and the replaced portions of fossils.

A statement often made is that chert horizons are associated with the slope of the present land surface, and certainly if weathering gives rise to chert, such chert should parallel the erosion surface. If the underlying formation were horizontal, the chert horizon, on the slopes, should *cross the ends* of the formation. That this is not true is known by all, for the chert (whatever its form) conforms to the structure of the rocks associated with it. In fact, the structure of parts of the chalk in England was determined from the position of the flints. Numerous highway cuts throughout the United States have revealed the layers of chert in the residual clays continuing unchanged into and through hills of the solid rock. In such exposures, one can prove that the chert in the solid rock is absolutely continuous and identical with that of the weathered residual material. Weathering has liberated the chert formed syngenetically, not produced it.

The surface of an exposed fossiliferous limestone is commonly covered with fossils. In some formations, the embedded parts are calcareous and the exposed parts siliceous.[824] Silicification of this kind must not be confused, however, with the relative increase of silica in a rock after removal of the carbonates or other substances by solution.

According to Van Hise and Leith,[825] some of the Pre-Cambrian cherts of the Lake Superior region may be a consequence of the alteration of greenalite; the equation expressing the reaction follows:

$$4Fe(Mg)SiO_3 \cdot nH_2O + 20 = 2Fe_2O_3 \cdot nH_2O + 4SiO_2$$

This silica on release might be deposited at or near the place of alteration.

Ulrich[826] seems to have been the first to suggest rock weathering as an

[824] Bassler, R. S., Proc. U. S. Nat. Mus., vol. 35, 1908, p. 135.

[825] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region, Mon. 52, U. S. Geol. Surv., 1911, p. 530.

[826] Bain, H. F., and Ulrich, E. O., Bull. 267, U. S. Geol. Surv., 1905, pp. 27 and 30.

explanation for the origin of chert. He regarded the chert of the Lower Paleozoic in Missouri as being due to a concentration of the silica by ordinary chemical weathering, giving as his reason that the greater amount of chert on the gentle slopes proved that it was so formed. What Ulrich was really observing was the greater accumulation of *residual* chert on a gentle slope than on a steep slope. As Ulrich's deduction has been cited so often by advocates of this view, it will be well to evaluate it. If a horizontal limestone containing 15 per cent of chert underwent chemical denudation, it is evident that all the chert in the beds would be concentrated at the surface as the insoluble material of the limestone. This would be the maximum quantity of chert. Increasing slightly the slope of the eroded surface would increase the carrying power of the runoff, so that at first the smaller pieces of residual chert would be removed. As the slope was increased further, more and more fragments would be carried away until finally at a vertical cliff all the chert loosened by weathering (largely mechanical) would accumulate at its base as talus or be carried away by a stream. The solid floors of chert in some valleys in the Ozark area of Missouri and in the southern Appalachian area are evidence of the activity of the streams in mechanically removing the chert. Thus to ascribe the chert on the gentler slopes to the longer and slower processes of chemical weathering is not a safe assumption as the chert could have been (and probably was) originally present in the limestone. Tarr[827] studied in detail both of the formations described by Ulrich and found an abundance of drusy quartz and some chert in the Potosi formation and a far greater abundance of nodules, lenses, and beds of chert (some of the beds are nearly 10 feet thick as shown by well logs) in the Gasconade. The chert was visible in excellent vertical exposures and was also encountered in wells. Throughout the Ozark area, chert is abundant in exposures of the Gasconade and has been encountered in hundreds of well logs so the chert is evidently as widespread as the formation. Furthermore, fragments and pebbles of the chert from these formations occur in conglomerates above them.

B. Chert formed contemporaneously with the accumulation of the materials of the enclosing rock has been thought to result either from (1) *organic* or (2) *inorganic* precipitation of silica.

(1) Chert of *organic origin* is assumed to form from the shells of siliceous organisms which undergo partial solution. This and any other dissolved silica are assumed to cement the undissolved portions. That silica does undergo removal is proved by the replacement of siliceous shells by calcite. The fact that many cherts and flints contain the siliceous shells of organisms

[827] Tarr, W. A., The barite deposits of Missouri, Univ. of Missouri Studies, vol. III, No. 1, 1917.

has been considered evidence of their organic origin, but it remains to be proved whether such occurrences are genetic or merely incidental.

The radiolarian cherts of the Jurassic of California and the diatomaceous cherts of the Monterey shales of the same state have been stated to be of organic origin, but in the former it seems fairly certain that the radiolarian shells are incidental.[828]

Siliceous sponge spicules have long been regarded as the source of the silica in chert and flint. Hinde[829] has been the chief exponent of this view and has written extensively upon the subject. Tarr[830] made a careful study of the material Hinde had studied (in some cases having identical materials), and found that sponge spicules were consistently absent from most slides. The Upper Greensand on the Isle of Wight has several beds containing sponge spicules. Some cherts occur in them. These beds also contain glauconite and quartz grains. The chert has the characteristics of a chemically deposited bed, which includes the sponges, glauconite, and sand. This deposit might have been due to rapid precipitation near the mouth of a river where the fresh and salt water met. The high silica content of the waters made conditions favorable for the growth of sponges. The spicules are still amorphous or opaline silica. Sponge spicules are singularly absent from the chalk. The Rex chert of Idaho has local basal beds largely composed of spicules of siliceous sponges.[831] These spicules may be present because a siliceous sea water favored the growth of sponges, and hence their remains in the chert are incidental just as are fossils in a limestone.

The view of the organic origin of flint and chert was also supported by Van Hise,[832] Geikie,[833] de Lapparent,[834] Sollas,[835] Wallich,[836] and others. Nearly every supporter of the organic theory, however, has considered that there is more or less subsequent alteration and rearrangement of the silica, and that chert and flint may also be formed in other ways.

[828] Fairbanks, H. W., San Luis Folio, No. 101, U. S. Geol. Surv., 1904, p. 244; Davis, E. F., op. cit.

[829] Hinde, G. J., Sponges in the Lower and Upper Greensand of the south of England, Phil. Trans. Roy. Soc., vol. 176, pt. ii, 1885, p. 403; On the organic origin of the chert in the Carboniferous Limestone Series of Ireland and its similarity to that of corresponding strata of North Wales and Yorkshire, Geol. Mag., vol. 24, 1887, pp. 435–446; On the chert and siliceous schists of the Permo-Carboniferous strata of Spitzbergen, etc., Geol. Mag., vol. 25, 1888, pp. 241–251.

[830] Tarr, W. A., Origin of chert and flint, Univ. of Missouri Studies, vol. 1, no. 1, 1926, pp. 8–9.

[831] Mansfield, G. R., Prof. Paper 152, U. S. Geol. Surv., 1927, p. 368.

[832] Van Hise, C. R., Treatise on metamorphism, Mon. 47, U. S. Geol. Surv., 1904, p. 819.

[833] Geikie, A., Textbook of geology, vol. 1, 1903, p. 179.

[834] de Lapparent, A., Traité de géologie, vol. 2, 1906, p. 687.

[835] Sollas, W. J., Age of the earth, 1912, pp. 163–165.

[836] Wallich, G. C., A contribution to the physical history of the Cretaceous flints, Quart. Jour. Geol. Soc., vol. 36, 1880, pp. 68–92.

A modification of the theory as outlined above assumes that some of the organic silica after deposition ultimately became a gel, and in this condition collected in depressions on the sea or lake floor, thus giving rise to the lenticular shapes of the nodules.

(2) The *inorganic origin* of syngenetic chert was first proposed by Prestwich.[837] Jukes-Browne and Hill[838] rejected the idea because of the then current view that silica could not be precipitated from sea water except by organic agencies. Tarr explained the inorganic theory in detail and proved experimentally that it is possible for chert to develop in this way. As outlined by Tarr,[839] the theory is as follows: the silica contributed to the sea accumulates (the accumulation is made possible by the stabilization of the colloidal silica particles) until its concentration causes it to be precipitated as a gel, the particles of which on settling to the bottom are aggregated into globular and ellipsoidal masses following the ordinary tendency of gels to assume globular forms that eventually become nodules and lenses of chert or flint. If the quantity of silica is large enough and the rate of precipitation sufficiently rapid, a continuous layer or bed would be deposited. Successive periods of accumulation, concentration, and precipitation at varying intervals would give rise to successive layers of nodules, lenses, or beds.

After the silica gel has been aggregated into globular forms on the sea bottom, further growth is assumed to take place through direct additions of silica from the water, and nodules partially buried in muds may replace or displace the adjacent materials. Such an origin by replacement or displacement verges upon the penecontemporaneous type. If other sediments accumulate rapidly, the growth of nodules might continue only as protuberances. A slowing up in the rate of accumulation of surrounding materials might permit the expansion of the protuberance into another nodule above the first. Protuberances or other irregularities in the shape of nodules might be caused also by varying rates of growth of the nodules themselves due to variable amounts of silica available for growth. Nodules may not have attained full size before burial, but the absence of evident displacement adjacent to them and the assumed difficulty of the penetration of calcareous muds by siliceous solutions are thought to render it doubtful that much material was added to the nodules after burial. The addition of silica to a buried nodule with a consequent enclosing of calcareous material around it, the precipitation of silica and calcium carbonate together before burial, or the migration of calcium carbonate into the silica gel may explain the gradation of chert into limestone and also the abundance of calcite in parts of some chert nodules.

[837] Prestwich, J., Geology, chemical, physical, and stratigraphical, vol. 2, 1888, p. 322.
[838] Jukes-Browne, A. J. and Hill, W., Quart. Jour. Geol. Soc., vol. 45, 1889, p. 419.
[839] Tarr, W. A., op. cit., 1917; op. cit., 1926.

If the water containing the globular masses of silica gel was shallow enough (some chert nodules formed in shallow water, as they occur with oolites which are known shallow-water deposits), currents might roll the gel masses about, whereupon more material would be added to them and concentrically banded nodules would result. Concentric banding in chert nodules is commonly due also to different rates of growth in individual nodules; a slow rate of accumulation of silica resulting in a greater accumulation of organic matter in the same amount of silica, which would be evident as a darker band in the nodule. As the masses of gel hardened, some of them might crack and portions of the surrounding calcareous mud would penetrate the cracks. The cherts and flints that show faulting were broken while still a gel, for the parts are displaced and yet have reunited along these broken surfaces. This property of breaking and reuniting is characteristic of silica gels. Ultimately, the globular masses of gel were buried; and, due to the weight of the overburden, most of them were flattened into lenticular shapes. Subsequently, dehydration and crystallization (a slow process) changed the gel to chert and flint.

Organisms were buried in the precipitated silica by falling into it from above; growing on it as a part of the sea floor; being picked up by a nodule as it was rolled about; or being enclosed as a mass of the gel spread over them. They might be distributed throughout the silica mass or be confined to the outer portion. The common excellent preservation of fossils in cherts as compared with those in the enclosing rock shows that burial took place soon after the death of the organisms, thereby insuring their protection from scavenger animals, solution work, or wave action. Annelid borings in chert nodules in the Middle Cambrian are reported by Walcott.[840] These were undoubtedly made while the chert nodule was still soft, which proves that it was formed at the same time as the enclosing beds.

It is thought that peneplaned or base-leveled lands, that is, lands supplying little arenaceous or clayey sediments, are necessary for the syngenetic formation of flint and chert deposits of any magnitude and purity, since high and dissected lands would furnish too much mud and sand to the sites of deposition, and the precipitated silica would thus be disseminated throughout the clastics.

Silica that is brought to the sites of deposition by hot springs of magmatic or other origin might arrive in sufficient quantities to form entire beds, and the high temperature of the waters together with the presence of iron might lead to the formation of iron silicates (greenalite), or cherts high in iron salts. Doubt has been expressed as to the adequacy of springs or

[840] Walcott, C. D., Fossil medusæ, Mon. 30, U. S. Geol. Survey, 1898, pp. 17–21.

other magmatic sources to contribute a quantity of silica sufficiently large to form such great quantities of chert as those in the iron formations of the Lake Superior region.[841] Nevertheless, it certainly could be done if the conditions of supply were maintained long enough. Gruner[842] and Moore and Maynard,[843] in advocating an origin by direct chemical precipitation for the cherts of the Lake Superior region, have presented evidence indicating that the silica necessary for their formation could have been derived through the normal processes of weathering. Sargent has advocated a similar source for the silica of the chert (which he explains has been precipitated on the sea floor) in North Wales (Flintshire) and of the Lower Carboniferous in Derbyshire. Tarr and Twenhofel regard the great quantity of chert in the Boone formation of Missouri and Oklahoma and in several of the Pennsylvanian formations of Kansas as having originated syngenetically by direct precipitation in sea water and the silica as having been derived through normal weathering processes. Mansfield,[844] likewise, favors a peneplaned land surface as the source of the silica in the widespread bedded cherts of the Rex formation, which he regards as being due to chemical precipitation on the sea floor.

Various objections have been raised to the theory of the direct inorganic precipitation of silica to form nodular cherts. The more important objections and the replies thereto are as follows: (1) it is claimed that the arching of the beds shows growth of the nodules subsequent to the deposition of the enclosing beds. It has been proved, however, that such arching occurs also over any object on the sea floor. (2) Objection is made that the method of precipitation is inadequate, but experimental proof has shown that direct precipitation can occur, and the rapid disappearance of the silica on reaching the sea proves that it has occurred in the sea water. (3) It is claimed that the silicification of fossils shows that replacement does occur. The abundance of unreplaced calcareous fossils both within and without chert nodules shows, however, that even this sort of replacement is unusual. Moreover, the fact that calcareous fossils can be buried in the silica gel without being replaced is a strong argument against replacement. (4) It is said that the shapes of nodules are never due to rolling on the sea bottom. It is not thought, however, that the shape of nodules was due primarily to rolling, but only that their initial globular form (normally assumed by gels) was possibly accentuated by rolling. Rolling would prob-

[841] Gruner, J. W., The origin of sedimentary iron formations, etc., Econ. Geol., vol. 17, 1922, pp. 407–460.

[842] Gruner, J. W., op. cit., pp. 452–460.

[843] Moore, E. S., and Maynard, J. E., Econ. Geol., vol. 24, 1929, pp. 520–527.

[844] Mansfield, G. R., Econ. Geol., vol. 26, 1931, pp. 371–374.

ably not have taken place had not the original form been rounded. The association of chert nodules with formations that are cross laminated, with oolites, and with mud-cracked beds is ample proof, however, of shallow-water conditions which would permit the presence of currents to produce the rolling. (5) The objection is made that no chert in the initial stages of formation has ever been observed under natural conditions. This has not been possible because deep-sea studies have not been sufficiently extensive, and because physiographic conditions on the lands bordering existing shallow waters permit the entrance of great quantities of mud and sand which carry the silica down with them. The wide flats of calcareous muds adjacent to the Bahamas would be favorable sites for the formation of chert today if those flats were adjacent to a land mass that could furnish the silica.

The theory of a syngenetic origin for chert and flint by direct chemical precipitation on the sea floor explains the distribution of chert nodules and lenses along planes, their repetition along successive horizons, their generally lenticular shapes, the occurrence of widespread beds of chert, the occurrence of calcareous fossils and areas within chert, the irregular shape of the nodules, the gradation of the chert into the enclosing rock, and many other physical features of chert. The theory accounts for the widespread distribution of chert in a given formation, for its localization near shore and adjacent to possible deltas, for the source of the silica, and lastly furnishes a satisfactory method of precipitation.

(C) The third theory of the origin of chert and flint has been designated as proving a syngenetic origin though it postulates their formation penecontemporaneously with the deposition of the other sediments. According to this theory, the silica is first precipitated and deposited (supporters of the theory do not state by what agency precipitation is brought about) on the sea floor along with the materials of the enclosing rock, just as is advocated under the direct-chemical-precipitate theory just discussed. After the deposition of silica and calcium carbonate, however, the silica is supposed to go into solution and then to be reprecipitated and redeposited, displacing or replacing surrounding sediments as this takes place, and eventually to become the chert and flint nodules. Why this additional stage or process of solution following the initial chemical precipitation should take place, it would be hard to say, especially as the dissolved silica is then supposed to be again precipitated and deposited in like manner as before. This theory can in no way account for great bedded deposits like the Lake Superior cherts and even its advocates use it only in explaining the origin of nodules.

In England, this theory of origin has received the support of Jukes-Browne and Hill, who explain some of the cherts of the Cretaceous in this way.[845]

[845] Jukes-Browne, A. J. and Hill, W., Quart. Jour. Geol. Soc. vol. 45, 1889, pp. 403–421.

Likewise, Hull and Hardman[846] explained the Carboniferous cherts of Ireland as a result of the replacement of unconsolidated sediments, and the Carboniferous cherts of Belgium have been assigned to the same origin by Renard.[847] In America, this theory of origin has received the support of Cleland,[848] Van Tuyl,[849] and others.

SUMMARY OF ORIGIN. The immense volume of silica carried by rivers annually to the sea and the great abundance of chert and flint in all the geologic systems show that this type of sedimentary deposit is of primary importance.

It is believed that the silica of chert and flint in the form of nodules, lenses, and beds was deposited directly from the sea water usually under conditions of a slow rate of accumulation. A certain amount of silica replacement of the calcium carbonate surrounding the soft nodules as they rested on the sea floor among the other accumulating sediments may have taken place, also. Likewise, it is possible that some chert and flint have been formed by replacement of consolidated rock by silica which was obtained through a leaching of the rock by ground water or through the process of weathering. The quantity so formed was probably not large, however,

Research Needed

More research upon the chert and flint problem is very advisable. Detailed investigations should be made of what happens to silica in "solution" in fresh waters when they mingle with sea waters. The sea bottoms at such places should be studied to learn the condition of the silica in the sediments as they are deposited. Studies of areas where calcareous deposits are accumulating should be made as these areas are promising sites for the deposition of silica. However, the worldwide high relief of the continents of the present day with the resultant mechanical rather than chemical erosion is unfavorable to an accumulation and precipitation of silica in the sea, as the silica carried seaward by the present streams is being deposited with the abundant argillaceous muds. Therefore, of course, present times are not favorable for observing chert in process of formation. From the field point of view, it is essential that more care be devoted to observation of the field relations of chert and flint nodules to the enclosing rocks. The recognition that chert and flint are present in a deposit bears little on the problem of their origin, but the relationships of the nodules to each other and the enclosing rock, the nature and character of the banding of the nodules and their other structures, the distribution and preservation of

[846] Hull, E. and Hardman, E. T., Sci. Trans. Roy. Dublin Soc., vol. 1, 1878, pp. 71–94.
[847] Renard, M. A., Bull. d. l'Acad. Royale de Belgique, 2 S., T. 46, 1878, pp. 471–498.
[848] Cleland, H. F., Geology, physical and historical, 1916, p. 77.
[849] Van Tuyl, F. V., The origin of chert, Am. Jour. Sci., vol. 45, 1918, pp. 449–456.

fossils in the nodules and their similarities and dissimilarities to those in the enclosing rocks, any changes in the nodules from center to periphery, the presence of nuclei, the relation of the nodules of one zone to those of others in the same vertical section, structures in the chert which are also in the enclosing rock; these are all characters of significance with respect to the problem of the origin of chert and flint.

Phosphatic Sediments[850]

GENERAL

Phosphorus has wide and most abundant distribution in the igneous and crystalline rocks as a constituent of apatite. It is also present in the more rare monazite and xenotime, and there are occurrences in still rarer minerals. From these minerals of original occurrence it is released in decomposition, and being taken into solution is carried to the sea or other site of deposition. It is probably transported as phosphoric acid and as calcium phosphate. The latter is soluble in carbonated waters[851] and in swamp waters rich in organic matter; it is precipitated in the presence of calcium carbonate, and hence natural waters acting upon a deposit of the latter and calcium phosphate would remove the carbonate unless these waters contained substances increasing the solubility of the phosphate. Some phosphorus-containing material is probably carried as colloid.

There are many phosphatic minerals formed by sedimentary processes, the greatest numbers of which exist or are formed in guano. Most of these probably are rare in other sedimentary phosphate deposits, of which the composing minerals, however, are not always known. Collophanite ($Ca_3P_2O_8 \cdot H_2O$) is known to be present and also dahllite ($Ca_6(PO_4)_4 \cdot CaCO_3 \cdot \frac{1}{2}H_2O$).

Phosphorus in solution is precipitated or taken out of solution largely through organic agencies; vertebrates, brachiopods, annelids, crustaceans, and a few others being important in this work. Some reacts with materials on the sea bottom, forming various phosphates. Phosphorus may also be precipitated through bacterial action, as it has been shown that some bacteria contain phosphorus in their tissues.[852]

[850] The manuscript for the first edition was prepared by Doctor Eliot Blackwelder, but the state of Doctor Blackwelder's health precluded his assistance in the preparation for the manuscript for the present edition. The material of the first edition has been freely used.

For a bibliography on phosphate deposits to 1888, see Penrose, R. A. F., jr., Bull. 46, U. S. Geol. Surv., 1888. Information to date of 1928 may be found in Les reserves mondiales en phosphates, 2 vols., many authors, and published as a part of the work of the Fourteenth International Geological Congress, Madrid, Spain, 1926.

[851] Müller, R., Jahrb. k. k. Reichsanstalt, vol. 27, Min. pet. Mitth., 1877, p. 25.

[852] Alilaire, M. E., Sur la présence du phosphorus dans la matière grasse des microbes, Compt. Rend., Paris Acad. Sci., vol. 145, 1907, pp. 1215–1217.

CLASSES OF SEDIMENTARY PHOSPHATIC DEPOSITS

All varieties of sedimentary phosphatic deposits grade insensibly into each other, but for purposes of description, they may be placed in two classes, primary and secondary, with subdivisions as shown.

A. Primary
- Stratified marine phosphorites
- Nodules in clay, greensand, etc.
- Guano

B. Secondary
- Leached phosphatic deposits
- Phosphatized rocks
- Detrital deposits

Primary Phosphatic Deposits

STRATIFIED MARINE PHOSPHORITES. The stratified marine deposits of calcium phosphate are generally known as phosphorite. In composition, the purest approach apatite, but unlike that mineral they seem amorphous and exist in compact, powdery, oolitic, and concretionary or nodular forms. They are known in the Mississippian and Permian formations of the Rocky Mountains in the United States, the Devonian of Tennessee, the Tertiary of Tunis and Algiers, the Cretaceous at Taplow in England, and in other occurrences of greater or less importance. The range in the geologic column is from Cambrian to Pleistocene, and in quantity they outrank all other types of phosphatic deposits.

Deposits of bedded marine phosphorites extend over areas of thousands of square miles in formations of comparatively uniform thickness. Associated strata consist of black shales, cherts, limestones, dolomites, and sandstones. The phosphorite units range in thickness from a fraction of an inch to many feet, the range in those of southeastern Idaho being to about 30 feet for beds of good phosphate, but such units are accompanied by other beds of shales and limestone which contain more or less phosphate. Individual beds range in thickness from about 1/16 inch to 6 or 8 inches, most being less than 1 inch thick and the average maximum 2 to 3 inches. The bedding in the western United States phosphorites is described as regular and even, devoid of such features as mud cracks, ripple marks, rain impressions, current and rill marks, and cross lamination.[853] Beds of phosphatic shale and impure limestone are interstratified with the phosphorites, the separation in some instances being sharp and in others not. Streaks of shale occur in some of the phosphate beds, and streaks of phosphate and phosphatic nodules are present in shales and sandstones. Some beds of phosphate pass laterally into sandstone, and sandy streaks extend into phos-

[853] Mansfield, G. R., Prof. Paper 152, U. S. Geol. Surv., 1927, p. 361.

phate beds. These variations indicate shallow waters and nearness to the regions of supply of terrigenous materials. The reasons for the variations in quantity and nature of materials supplied remain to be determined.

The Rocky Mountain phosphorites, which more or less typify others, are characterized by gray, brown, or black colors, depending on hydrocarbon matter present; have a strong bituminous odor and, in some cases, oolitic texture; weathered fragments have a characteristic bluish-white bloom and commonly white reticulate markings. In some occurrences, as near Lander, Wyoming, a phosphorite bed is saturated with petroleum. The phosphatic beds are sparingly or not at all fossiliferous, a few discinoid brachiopods, gastropods and fish-bone fragments being the fossils commonly found, and all are phosphatized. The associated strata carry fossils in greater or less abundance, consisting of bryozoans, corals, brachiopods, mollusks and calcareous algæ.[854] The section which follows shows the detailed character of the phosphorite and associated strata of the Permian Phosphoria formation at a locality in southeast Idaho.[855]

Rock character	*Thickness*	
Shale, dark brown, not fetid	1 ft.	10 in.
Phosphatic rock, gray, oolitic, nodular, P_2O_5 36.3 per cent	1	0
Shale, brown, finely oolitic		5
Phosphatic rock, gray, coarsely oolitic, nodular, P_2O_5 36.7 per cent		8½
Shale, brown, part finely oolitic		2½
Clay, yellow, sandy, contains concretions		8
Phosphate rock, brown, medium oolitic, P_2O_5 35.3 per cent		5
Shale, dark brown, phosphatic		2
Phosphatic rock, dark brown, medium oolitic, P_2O_5 29.4 per cent		5
Phosphate rock, gray, coarsely oolitic, P_2O_5, 35.9 per cent	1	2
Shale, dark brown to black, finely oolitic		3
Phosphate rock, coarsely oolitic, P_2O_5 35.9 per cent		4
Shale, brown, sandy		1
Phosphate rock, medium oolitic		1½
Shale, brown, finely oolitic		5
Phosphate rock, black, medium oolitic		2
Shale, brown, calcareous		4
Phosphate rock, black, sandy, medium oolitic		1
Shale, brown, oolitic in thin streaks		2
Phosphate rock, gray, coarsely to finely oolitic, P_2O_5 33.2 per cent		11

[854] Branson, C. C., Paleontology and stratigraphy of the Phosphoria formation, Univ. Missouri Studies, vol. 5, 1930, pp. 1–99. This paper contains a rather complete bibliography of the Rocky Mountain phosphates.

[855] Mansfield, G. R., op. cit., 1927, p. 77.

Rock character	*Thickness*	
Phosphate rock, shaly, gray, finely oolitic		3 in.
Phosphate rock, brown, medium oolitic		4
Shale, brown, $1\frac{1}{4}$ inch streak near base oolitic		6
Phosphate rock, shaly in places, dark brown, coarsely to finely oolitic, P_2O_5 33.2 per cent		9
Phosphate rock, gray, coarsely oolitic, $\frac{1}{2}$ inch shale near base, P_2O_5 37 per cent	1 ft.	1
Limestone, drab, impure		5
Phosphate rock, medium to finely oolitic		3
Shale, brown		9
Phosphate rock, dark gray, coarsely oolitic		2
Shale, brown		3
Phosphate rock, thin shale partings, dark gray, coarsely oolitic, P_2O_5 30 per cent		10
Limestone, lenticular		10
Phosphatic rock, dark brown, medium to finely oolitic, P_2O_5 26.1, per cent	9	8
Shale, black, in part finely oolitic	3	
Shale, brown	1	8
Shale, black, phosphatic, in part finely oolitic	6	6
Shale, brown, contains concretions		10
Shale, rusty brown to yellow, contains concretions	1	8
Shale, dark brown, phosphatic in places, contains concretions	16	6
Pebbly or concretionary bed		4
Shale, brown	1	2
Shale, black to dark brown		9
Pebbly or concretionary layer, phosphatic		3
Shale, black, slightly oolitic		7
Shale, contains pebbles or concretions		6
Shale, brown	3	4
Pebbly or concretionary bed		4
Shale, brown	2	3
Pebbly or concretionary bed, phosphatic?		6
Shale, brown, phosphatic	2	6
Shale, black		6
Clay		10
Shale, brown	1	0
Shale, black to light brown, slightly phosphatic	11	0
Limestone, contains some shale	6	0
Shale, slightly phosphatic	21	0
Shale, black, phosphatic	5	6
Shale, brown	1	0
Limestone, lenticular		8
Shale, dark	15	0
Phosphate rock	3	0
Soil, black, fetid	9	0
Shale, black, phosphatic, finely oolitic	5	6
Shale, brown, somewhat phosphatic	15	0

Rock character	*Thickness*	
Limestone, dark gray	3 ft.	0 in.
Phosphate rock, dark brown, medium oolitic, high grade and represents the thickest and richest bed	7	0
Shale, brown	1	0
Limestone, white, not measured		
	175	2½

The section shows the thickness of the individual beds and the nearly maximum thickness of the phosphate member. It will be noted that many of the beds are oolitic. These oolites are more or less spherical with many

TABLE 82

	1	2	3
Insoluble	10.00	1.82	2.62
SiO_2	0.00	0.30	0.46
Al_2O_3	0.89	0.50	0.97
Fe_2O_3	0.73	0.26	0.40
MgO	0.28	0.22	0.35
CaO	45.34	50.97	48.91
Na_2O	1.10	2.00	0.97
K_2O	0.48	0.47	0.34
H_2O	1.04	0.48	1.02
H_2O plus	1.14	0.57	1.34
CO_2	6.00	1.72	2.42
P_2O_5	27.32	36.35	33.61
SO_3	1.59	2.98	2.16
F	0.60	0.40	0.40
Cl	Trace	Trace	Trace
Organic matter	Not determined	Not determined	Not determined
	96.51	99.04	95.97

1. Phosphate from main phosphate bed, 2½ miles east of Cokeville, Wyoming.
2. Dunnellon claim, Crawford mountains, Utah.
3. Preuss Range, 8 miles east of Georgetown, Idaho.

Analyses by Steiger, U. S. Geol. Surv.

more or less irregularly flattened. They have a roughly concentric structure and range from mere specks to ½ inch in diameter, and scattered nodules up to 2 inches in diameter occur locally. They are generally darker than the matrix, and a few possess a dark shiny coating. The color ranges from gray to black and is generally dark brown. Some beds contain pebbles derived from earlier formed oolitic phosphates of the Phosphoria formation.

Table 82 gives the chemical composition of some beds of the Rocky Mountain phosphorites.

The analyses show the high content of calcium phosphate. The insoluble matter consists mainly of silica with minor quantities of kaolin. The carbon dioxide may be united with some of the lime to form calcite, but it also may be united with lime and phosphoric acid. The mineral composition has not been worked out, but according to Schaller the best that can be said is that the oolites are composed of an amorphous mineral, probably collophanite, and some of them are surrounded by a thin coating of crystallized mineral which may be one or more of several phosphate minerals.[856]

In most localities the richer phosphorite beds consist of small roundish grains or pellets whose composition is as given above. The granules are not altogether like those of typical oolites of limestones. Many have concentric structure; radiate structure has not been observed. The zonal or concentric structure is best shown in the outer portions, but some show it throughout. Mansfield states that the phosphatic grains are true oolites.[857] Many of the particles, however, have little or no concentric structure, and in others the zonal structure is confined to the periphery, the entire particle or central portion in these cases being composed of speckled and more or less granular or amorphous brown material whose original nature has not been determined. It has been suggested by Blackwelder that these may represent excretory pellets of such animals as fishes and holothurians.[858] Some of the oolites show a nucleus, but in most such seems to be wanting. Small grains of quartz are irregularly distributed through some oolites and some particles.

In some beds the oolites or granules are mingled with fragments of vertebrates and invertebrates. Some of these were originally phosphatic; others carried no phosphate in the beginning, but subsequently became phosphatized. The phosphatic shells appear to consist largely of a crystalline material which is probably the hydrous calcium carbophosphate, dahllite. Most beds contain a greater or less admixture of angular particles of quartz of the size of sand and silt grains. Marcasite (and pyrite) is a rather common accessory mineral, as should be expected from the hydrocarbonaceous matter present. The matrix of the phosphorite in most of the beds has composition similar to that of the oolites, but in others it consists of calcite, dolomite, or even chert.

Much has been written relating to the origin of the marine stratified phosphorites, and the problem has been only partly solved. Their interlamination

[856] Mansfield, G. R., op. cit., p. 367.
[857] Mansfield, G. R., op. cit., p. 361.
[858] Blackwelder, E., Treatise on sedimentation, 1925, p. 396.

with marine limestones, shales, and sandstones, and the presence of marine fossils within them, are thought to prove deposition in a marine environment. The high content of hydrocarbonaceous matter and the occurrence of marcasite show that this environment was one of reducing conditions. The replacement of shell and other organic matter, originally calcareous or only slightly phosphatic, by phosphate proves diagenesis and not direct precipitation for these portions, this probably taking place while the sediments were in a soft condition. The depth of deposition is not definitely shown by the phosphoritic beds, but their general character and that of the associated strata suggest shallow waters.

The rather uncommon occurrence of stratified marine phosphorites indicates that special and uncommon conditions are required for their formation. The fact that phosphate and glauconite occur in association above unconformities suggests more or less common conditions for the formation of the two types of sediments.[859] The conditions, however, are not identical, as glauconite does not seem to be present in the purest beds of phosphorite, but it is a common associate of associated calcareous beds, and the abundant occurrences of glauconite are low in phosphate. Benthonic organisms are essentially absent from the phosphorites, but Mansfield[860] shows in several of his sections that much phosphatized fragmentary shell matter is present. The absence of many benthonic organisms indicates bottoms not favorable for their presence, and this is supported by the commonness of hydrocarbonaceous matter. Undoubtedly, therefore, anaërobic and reducing conditions prevailed over and within the bottom deposits. It is possible that the waters above were abundantly aërated and populated by an abundant planktonic and pelagic fauna whose excretory pellets and excretions of indigestible shell fragments fell to the bottom to become phosphatized and furnish nuclei for oolites.

A part of the phosphorus in the phosphorites may have been derived from shell matter. This was first shown in 1854 by Logan and Hunt,[861] who demonstrated that the shells of *Lingula* and certain other marine organisms contain relatively large quantities of calcium phosphate. Later work by Clarke and Wheeler[862] shows this in greater detail (see table, p. 25). However, as the phosphorites are not composed in any large part of phosphatic shells, it is not possible to refer their origin directly to this source. Davies[863] described the concretionary-like structures of phosphatic particles and

[859] Goldman, M. I., Basal glauconite and phosphate beds, Science, vol. 56, 1922, pp. 171–173.

[860] Mansfield, G. R., op. cit., plates 67–70.

[861] Logan, W. E., and Hunt, T. S., Am. Jour. Sci., vol. 17, 1854, p. 236.

[862] Clarke, F. W., and Wheeler, W. C., Prof. Paper 124, U. S. Geol. Surv., 1922.

[863] Davies, D. C., Geol. Mag., vol. 4, 1867, p. 257.

presented the evidence for origin in shallow waters not subject to strong agitation. Sollas[864] in 1872 stated that many phosphatic nodules are pseudomorphs after sponges, shells, and other objects. The chemistry of the putrefaction of organic material was discussed in 1872 by Hudleston,[865] who showed that ammoniacal and phosphatic solutions are formed and under certain conditions calcium phosphate is precipitated. Teall[866] in 1875 described the experimental formation of phosphorites and pointed out that a thin unit of phosphorite ordinarily is represented elsewhere by a thicker unit of chalk or limestone. Penning and Jukes-Browne[867] noted the association between collophane coatings and decaying organic matter in the basal portions of shark teeth and the interiors of shells.

Several elaborate theories to account for the stratified marine phosphorites, each supported by detailed arguments, had been presented before 1900. Each has its merits, but no one seems to satisfactorily cover the entire problem. Renard and Cornet[868] in 1891 concluded that the phosphates had been precipitated from colloidal solutions derived from decay of organic matter under special topographic conditions. Lasne[869] presented a most elaborate theory involving special physiographic and climatic conditions on land and sea and the formation of particles of phosphatic matter at first enmeshed in floating vegetable matter, these particles afterward settling to the bottom. Murray[870] ascribed precipitation of the phosphate to ammonium carbonate solutions due to decay of accumulations of organic matter, produced by wholesale destruction of marine populations brought about by changes in the physical conditions of the waters beyond the endurance capacity of the organisms, and accumulation beyond the ability of scavenger utilization. He later cited the wholesale destruction of the tile fish in 1883, when this fish was killed by hundreds of millions along the Atlantic coast of the United States. Similar destruction on a large scale has been described by Oldham[871] and Blanford,[872] the instance noted by the

[864] Sollas, W. J., Quart. Jour. Geol. Soc., vol. 28, 1872, pp. 63–70, 76–81.

[865] Hudleston, W. H., Quart. Jour. Geol. Soc., vol. 31, 1875, pp. 376–385.

[866] Teall, J. J. H., The Patton and Wicken phosphate deposits, Cambridge, 1875.

[867] Penning, W. H., and Jukes-Browne, A. J., Geology of the neighborhood of Cambridge, Mem. Geol. Surv. England and Wales, 1881.

[868] Renard, A. F., and Cornet, J., Recherches micrographiques sur la nature et l'origine des roches phosphatés, Bull. Acad. Roy. de Belgique, vol. 21, 1891, p. 126–160.

[869] Lasne, H., Origine des phosphates de chaux de la Somme, Paris, 1901; Sur les terrains phosphatés des environs de Doullens, Bull. Soc. Géol. France, vol. 18, 1889–90, pp. 441–491.

[870] Murray, J., Changes of temperature in the surface waters of the sea, Geog. Jour., vol. 12, 1898, pp. 129–131.

[871] Oldham, R. D., Report on the Indian earthquake of June 12, 1897, Mem. Geol. Surv. India, vol. 29, 1899, p. 80.

[872] Blanford, W. T., Discussion of paper by Cornet, F. L., On the phosphatic beds near Mons, Quart. Jour. Geol. Soc., vol. 42, 1886, pp. 325–339.

former taking place in certain Indian rivers and being caused by earthquake shock, and that cited by the latter occurring on the Indian Malabar coast and being due to the change in monsoons.

Explanations of the origin of the phosphorites of western United States have been made by Gale and Richards,[873] Blackwelder,[874] Breger,[875] Pardee,[876] and Mansfield.[877]

Blackwelder directs attention to necessary special conditions of currents, temperature, and other factors, causing wholesale destruction of organisms whose decomposition produced ammoniacal solutions which dissolved phosphatic materials from bones, shells, etc. This was then reprecipitated to form hydrous calcium carbophosphates, locally replacing carbonates and enriching calcium phosphate in originally phosphatic shells, and in the main forming the nodules of the enclosing paste which now cements the beds of phosphorite. In the first edition of the present work Blackwelder referred the original character of the spherical particles to excrements. Breger considers the phosphates and oily shales to have a common origin in a micro-organic ooze, ascribing the oolites to rolling or to foraminifera, while the phosphates are thought to have been taken from sea water by bacteria. Pardee appealed to low temperature, known to have existed in the Permian, to account for failure of decomposition and also to prevent escape of carbon dioxide formed from organic decay and derived from the atmosphere. The presence of the gas in abundance in the sea water dissolved such carbonates as were formed or transported to the region, and this permitted the phosphates to accumulate as insoluble residue of a far larger original precipitation. Mansfield at first considered the oolites as originally composed of calcium carbonate and to have been replaced by phosphate in colder waters. His latest statement relating to origin is as follows:[878]

[873] Gale, H. S., and Richards, R. W., Preliminary report on the phosphate deposits in southeastern Idaho and adjacent parts of Wyoming and Utah, Bull. 430, U. S. Geol. Surv., 1910, pp. 457–535.

[874] Blackwelder, E., Phosphate deposits east of Ogden, Utah, Bull. 430, U. S. Geol. Surv., 1910, pp. 536–551; The geologic rôle of phosphorus, Am. Jour. Sci., vol. 42, 1916, pp. 285–298; Origin of the Rocky Mountain phosphate deposits, Bull. Geol. Soc. Am., vol. 26, 1915, pp. 100–101 (Abstract). The geologic rôle of phosphorus, Am. Jour. Sci., vol. 42, 1916, pp. 285–298.

[875] Breger, C. L., Origin of the Lander oil and phosphate, Min. and Eng. World, vol. 35, 1917, p. 632.

[876] Pardee, J. T., The Garrison and Philipsburg phosphate fields, Bull. 640, U. S. Geol. Surv., 1917, pp. 225–228.

[877] Mansfield, G. R., Origin of the western phosphates of the United States, Am. Jour. Sci., vol. 46, 1918, pp. 591–598; Geography, geology, and mineral resources of part of southeastern Idaho; Prof. Paper 152, U. S. Geol. Surv., 1927, pp. 75–77, 187–188, 208–214, 361–366; Econ. Geol., vol. 26, 1931, pp. 353–374.

[878] Mansfield, G. R., op. cit., p. 366.

The phosphatic oolites, which constitute so large a proportion of the phosphate beds, were probably formed directly by biochemical and physical agencies from phosphatic solutions or colloids on the sea bottom. This material may have been supplied by some accidental wholesale destruction of animal life, but more probably it represents a slow gathering and concentration of phosphatic debris under conditions which largely excluded oxygen from the deeper waters and were thus unfavorable for forms of life that ordinarily inhabit the sea bottom and prevent the accumulation of organic debris. These conditions were induced by the considerable separation of the waters of the Phosphoria sea from the ocean and by the restriction in the circulation of its waters caused by this separation and by the supposedly smaller temperature differences which then existed between high and low latitudes. Generally cool temperatures with some climatic oscillations prevailed during the time of deposition of the phosphate. These conditions tended to favor the growth of plant and animal life in the shallower waters, while at the same time they reduced the activities of denitrifying bacteria, which curtail plant life and thus hinder the growth of animals dependent upon plants. Reduction of the activities of denitrifying bacteria may also have curtailed the precipitation of calcium carbonate, thus favoring the concentration of phosphatic solutions from which oolites might be formed. There was sufficient time for the postulated slow formation of the extensive phosphate deposits now found.

Phosphatic Nodules. Nodules containing more or less calcium phosphate, much seemingly in the form of collophane, are of rather common occurrence in some dark clays, shales, and greensands. Dimensions range from a few millimeters to about 6 centimeters in diameter. Shapes are irregular. Each, in general, has a more or less phosphatized nucleus or central portion, as a coprolite, shell, fragment of bone, etc., surrounded by concentric crusts of collophane. Shell cavities may be filled with the same material. Several of these nodules may become cemented to each other and to other substances to form a crust over the ocean floor. Many nodules are perforated in various directions by the boring of marine organisms, and they form excellent bases upon which benthonic organisms, as barnacles, oysters, bryozoa, algæ, etc., build and ultimately leave their skeletal structures to become phosphatized and form part of a nodule. Colors range from brown to black, largely from hydrocarbonaceous matter with which they are permeated. The surface of a nodule has a glazed appearance and a brownish or greenish color.

Phosphatic nodules have been dredged from the bottom of the Atlantic Ocean southeast of the United States, from the Agulhas Bank south of Africa in depths of 398 to 1500 fathoms, where they occur in association with greensand, and in deep water south of the bank in depths of 1900 fathoms in association with globigerina ooze, and on other parts of the continental slopes. The usual depths range from 200 to 500 fathoms.

According to Murray and Murray and Hjort,[879] they occur chiefly along

[879] Murray, J., and Hjort, J., The depths of the ocean, 1912, p. 159

coasts of which the waters are subject to great and rapid changes of temperature, these causing large-scale destruction of marine organisms. Phosphatic nodules are known in the geologic column from the Devonian-Mississippian black shales of eastern and central United States, the Permian Phosphoria formation of the Rocky Mountains, the Lower Cretaceous greensand near Cambridge, England, and many other terranes.

The content of calcium phosphate in nodules shows considerable range, but is relatively low. Analyses of two nodules dredged by the Challenger expedition off the south coast of Africa from depths of 150 to 1900 fathoms are given in table 83.[880]

With respect to the origin of phosphatic nodules, Murray and Renard[881] and Murray[882] suggest that an abundance of decaying organic matter favors

TABLE 83

	150 FATHOMS	1900 FATHOMS
P_2O_5	19.96	23.54
CO_2	12.05	10.64
SO_3	1.37	1.39
SiO_2	1.36	2.56
CaO	39.41	40.95
MgO	0.67	0.83
Fe_2O_3	2.54	2.79
Al_2O_3	1.19	1.43
Loss		3.65
Insoluble residue	17.34	11.93
	95.89	99.71

precipitation of phosphate. The fact that the nodules on the present sea bottom are merely calcium-phosphate cemented portions of sediments in which they occur is considered proof that they were formed in situ and not mechanically transported to the places of occurrence. The source of the phosphorus is sought in part in tests and shells of organisms and other organic matter which are assumed to have been brought into solution or to have been placed in the colloidal state by the decomposition products developed because of abundant organic matter. Ultimately the phosphorus is precipitated as the phosphate, some particle of matter, a shell, piece of

[880] Murray, J., Report on the specimens of bottom deposits, Bull. Mus. Comp. Zool., vol. 12, 1885, pp. 41–43, 52–53. Murray, J. and Renard, A. F., Deep sea deposits, 1891, pp. 396–400.

[881] Murray, J., and Renard, A. F., op. cit., pp. 391–400.

[882] Murray, J., The Maltese Islands with special reference to their geological structure, Scottish Geog. Mag., vol. 6, 1890, p. 481.

bone, or other substance serving as a nucleus. If adjacent matter is not removed, it becomes cemented into the nodule.

It is evident that the nodular deposits have much in common and, indeed, intergrade with the bedded phosphorites already described, and the conditions of their origins are believed to be rather similar. There is reason to think that these conditions range from certain peculiar situations on the sea bottom to those of coastal swamps.

Bonney[883] in 1875 concluded that the phosphatic nodules have been produced by phosphatization of various objects in the presence of ammonium carbonate and a weak solution of phosphoric acid on a muddy sea bottom, and that the conditions necessary for this reaction are somewhat complex and seldom realized. Gosselet[884] states that calcareous nodules, shells, and fragments of bone become more or less phosphatized and cemented in a matrix of variable character. Thus, phosphatic material, more or less resistant, may be reworked by marine currents to form local conglomeratic bodies and basal conglomerates of younger formations.

GUANO. *Primary*. Primary or true guano consists of the excrements of birds and other animals, accumulating in situations dry enough to retard bacterial decay and suited to the needs of vast colonies of birds. These conditions are best realized on low islands in the arid belts of the trade winds, the islands on the west coast of Peru,[885] Christmas Island in the Indian Ocean, and Navassa Island in the Caribbean being examples. Sea birds congregate in vast numbers on such islands, largely because they there are free from the depredations of foxes and other carnivorous animals of the mainland. In time the surface becomes covered with a layer of excrement and remains of dead animals. The thickness is variable on the same island and, of course, on different islands, but not infrequently a thickness of 10 to 20 feet has been attained.

Comparatively fresh guano is a dry pulverulent mixture of various organic compounds: phosphates, nitrates, and carbonates of lime, ammonia, and other bases (see analyses in table 84). From the time of its deposition it undergoes slow internal changes favored by the high temperature and assisted by the occasional rains. These changes gradually cause the elimination of the more volatile and soluble compounds, such as ammonia, the loss of the original structure, and a hardening of the deposit. During these processes many new minerals are produced in the interstices of the mass; most of these are hydrous phosphates, nitrates, and oxalates that are pe-

[883] Bonney, T. G., Cambridgeshire Geology, 1875.

[884] Gosselet, J., Des conditions dans lesquelles s'est fait le dépôt du chaux de la Picardie, Compt. Rend., Paris Acad. Sci., T. 123, 1896, p. 290–292.

[885] Penrose, R. A. F., jr., The nitrate deposits of Chili, Jour. Geol., vol. 18, 1910, p. 118.

culiar to guano deposits. Continuance of these changes eventually converts the guano and its foundation into firm rock. These are described on later pages as secondary phosphatic deposits. It is scarcely possible to draw a line of demarkation between primary and secondary, and yet it seems worth while to make such distinction.

Some guano is made in caves by bats. The deposits are not extensive, and the transformations through which bat guano passes seem to differ little from those occurring on bird islands.

TABLE 84

	1	2
SiO_2	0.64	
$FePO_4$, $AlPO_4$	1.04	1.04
$Ca_3(PO_4)_2$	18.22	83.47
"Organic matter"	5.90	
$MgNH_4PO_4$	4.00	
$(NH_3)_3PO_4$	0.90	
$(NH_4)_2SO_4$	1.82	
Ammonium urate	12.74	
NH_4Cl	1.55	
Oxalic acid	13.60	
Uric acid	21.14	
Resin	1.11	
Fatty acid	1.60	
K_2SO_4	3.30	
NaCl	2.44	
$CaSO_4$		0.37
$CaFl_2$		3.29
$MgCO_3$		0.44
$CaCO_3$		3.75
CaO		2.59
Moisture		1.70
Organic matter and combined water		3.30

1. Unaltered guano from the arid Chincha Islands off the coast of Peru (Analysis by Karmrodt).

2. Stone guano from Nauru Island, near Java (Analysis by Elschner).

Note: Although these analyses are not wholly comparable, they indicate clearly the loss of organic and soluble components and the concentration of calcium phosphates in the altered material.

Secondary Phosphatic Deposits

LEACHED PHOSPHATIC DEPOSITS. On the less arid bird islands, rain water soaks more or less copiously down through primary guano deposits and does its usual work of solution, aided by the fermenting action of bac-

teria. The different constituents of guano dissolve at different rates. Thus, the nitrates, oxalates, and carbonates, and ammonium phosphates pass out in solution much more rapidly than the less soluble calcium phosphate. Collapse and recementation of the honeycombed mass proceed until the result is a brecciated solid rock much richer in lime phosphates than the original guano. The material is generally light gray or white. Much of it consists of banded crusts of agate-like appearance, but there is no definite stratification and generally no fossils except bird bones.

The deposits of Nauru Island in the Java Sea are of this type. The analyses given in table 84 illustrate the difference between the primary guano and the altered product, or "stone guano." "Stone guano" is much more abundant than primary guano, and nearly all so-called "guano deposits" consist either of stone guano or phosphatized coral limestone, or of both these types and their intergradations.

The same general processes affect phosphatic materials other than guano. Some limestones contain appreciable quantities of phosphoric acid, generally in the form of grains of collophane, either scattered through the rock or segregated in thin layers. Under suitable conditions, and especially where such rocks have been elevated and subjected to the solvent action of descending ground water, the calcium carbonate dissolves more rapidly than the calcium phosphate, and the latter accumulates. These residual accumulations may reach considerable thicknesses. Examples of this type are found in Kentucky, Tennessee,[886] Belgium, France, and elsewhere, and they are usually closely associated with the more important phosphatized limestones to be described later.

A somewhat different type of leaching may occur in standing bodies of water where anaërobic conditions prevail and carbon dioxide is so excessively abundant that the lime carbonate goes into solution. Such effects upon previously deposited bottom sediments containing phosphoric acid might result in a thin layer of phosphorite being left as the sole residue of what otherwise would have become a thick bed of limestone. No proved example of this type is known, but instances have been reported from the chalk of England, northern France and Belgium, and from Balmez in Spain.

PHOSPHATIZATION OF OTHER ROCKS. Under suitable conditions various rocks have been extensively phosphatized by solutions carrying phosphoric acid downward through cracks and pores. Thus, coral and other limestones underlying deposits of guano have in many places been completely phosphatized,[887] and most of the guano islands of the tropics have such deposits.

[886] Hayes, C. W., Origin and extent of the Tennessee white phosphates, Bull. 213, U. S. Geol. Surv., 1903, pp. 418–423; Eckel, E. C., The white phosphates of Decatur County, Tennessee, Ibid., pp. 424–426.

[887] Sandberger, F., Neues Jahrb. f. Min., etc., 1870, pp. 306–310.

A similar change has been obtained in laboratory experiments. So rapid is the process under favorable conditions that on certain of the coral islands of the Pacific Ocean pure coral limestone has been completely phosphatized to depths of 2 to 3 feet in twenty years by the solutions derived from overlying deposits of guano. Elsewhere, marl and chalk beds containing scattered grains of phosphatic matter appear to have supplied phosphorus to descending solutions which have caused the substitution of phosphate for carbonate in limestone beneath. This appears to have been the origin of the most widespread and important of the Florida and Carolina phosphatic deposits, as well as many in France, Germany, and other countries. Analogous deposits have been found in caverns in France and elsewhere, the phosphorus in these cases having been derived from accumulations of bat guano.

In some instances rocks less susceptible to change than limestone have been thus converted into phosphates, D'Invilliers[888] describing the phosphatization of andesitic lava on Navassa Island in the West Indies. In this instance vivianite and other phosphates of iron and alumina were produced, rather than the usual tricalcium phosphate minerals.

DETRITAL PHOSPHATIC DEPOSITS. Like all other rocks, the various phosphatic beds are subject to disintegration and rearrangement by the various processes of transportation. In rather rare instances such processes yield deposits of sand or gravel which consist largely of phosphatic particles. The so-called "River Pebble Phosphates" of Florida appear to be of this origin, whereas the "Land Pebble Phosphates" are older beds of river gravel on terraces of flood plains. In such formations differential solution results in the more rapid abstraction of any particles of calcium carbonate that may have been included.

At certain localities in the Rocky Mountains of the United States the basal beds of the Permian, which are unconformable on the underlying strata, consist of calcareous shell fragments and abundant phosphate grains and nodules in a more or less sandy cross-laminated matrix. The cement of these deposits is not phosphatic, and they generally contain unphosphatized calcareous shells. The facts indicate that the phosphatized particles are detrital and were brought to their positions from other sources. The Lower Cretaceous Greensand of England contains phosphatized Jurassic ammonites which have been bored into by marine animals, and somewhat similar occurrences have been described from the Cretaceous of France, the Cambrian of Wales and England, and other regions.

[888] D'Invilliers, E. V., Phosphate deposits of the Island of Navassa, Bull. Geol. Soc. Am., vol. 2, 1891, p. 75.

THE SEDIMENTARY CYCLE OF PHOSPHORUS[889]

The phosphorus liberated in the decomposition of rocks on land generally finds its way in solution to the sea, where it is soon uniformly diffused. Ordinarily this dissolved phosphorus slowly passes through an intricate series of transformations from solution to solid form and back again through the activities of organisms. Plants absorb small quantities to incorporate in the nuclei of their cells. Animals devour the plants and make a similar use of the phosphorus, the higher forms using phosphates in making their shells, bones, and teeth. On the death of an organism, its remains are devoured by scavengers and decomposed by bacteria, with the general result that the phosphorus is returned to the oceanic solution.

From time to time, phosphorus escapes from this apparently endless circulation and becomes fixed in the sedimentary deposits. One well known method is through the agency of birds in the formation of guano and the secondary products derived therefrom.

In most situations, both on land and in the sea, the work of scavengers and bacteria is so effective that all dead organic matter is returned to solution. There are, however, a few environments where this process is more or less suppressed and modified because of the deficiency of oxygen. Such conditions exist in bogs, deep lakes, cul-de-sac bays, and other places where there is little circulation. It may also prevail in the muds beneath bodies of still water. In such situations anaërobic bacteria decompose organic matter, with the formation of hydrocarbons, ammonia, hydrogen sulphide, and other compounds. There is obviously much variation in the physico-chemical conditions. Under some conditions, which are but imperfectly understood, the phosphoric acid in solution interacts with lime carbonate to form collophane and probably other mineral phosphates. The element thus becomes fixed in the form of nodules or continuous beds of phosphorite. The sediments that accumulate in such places are of black or dark colors by reason of the hydrocarbon content.[890]

[889] Blackwelder, E., The geologic rôle of phosphorus, Am. Jour. Sci., vol. 42, 1916, pp. 285–298.

[890] In addition to the articles to which reference is made in the text, the following may be consulted with profit: Andersson, J. G., Über Cambrische und Silurische phosphoritführende Gesteine aus Schweden, Bull. Geol. Inst. Upsala, vol. 2, 1896, pp. 133–239; Blayac, M., Description géologique de la région des phosphates du Dyr et du Kouif, près Tebessa, Ann. des Mines (9 ser.), vol. 6, 1894, p. 319; Carnot, M. A., Sur les variations observeés dans la composition des apatites, phosphorites et des phosphates sédimentaires, Ann. des Mines, 10, 1896, pp. 137–231; Cayeux, L., Introduction à l'étude pétrographique des roches sédimentaires, Mémoires pour servir à l'explication de la carte géologique détaillée de la France, 1916; Clarke, F. W., Data of geochemistry, Bull. 770, U.S. Geol. Surv., 1924; Collet, L. W., Les concrétions phosphatées de l'Agulhas Bank (Cape of Good Hope), Proc. Roy. Soc. Edinburgh, vol. 25, 1905, pp. 862–893; Credner, H., Die Phosphoritknollen

Manganese in Sediments[891]

BY D. F. HEWETT

Manganese is a minor constituent in most sedimentary rocks. Like several other minor constituents such as phosphoric acid, barium, strontium, glauconite, etc., it is commonly present only to the extent of a small fraction of one per cent of most sediments, but here and there, the percentage rises considerably higher and in a few places nearly pure manganese oxides and carbonates form distinct beds that persist over large areas. By their rarity as well as their economic value, such occurrences assume uncommon interest.

The element manganese has numerous valences and therefore it forms numerous compounds with oxygen, chlorine, and sulphur, an unusually large part of which occur in nature. More than 200 minerals contain manganese as an essential element. The solubility of these minerals under natural conditions, as well as any influences that tend to change the valence of the element, play an important part in determining where and under what conditions the various manganese minerals decompose or are precipitated in sediments. The minerals that contain manganous oxide are more susceptible to solution than those which contain it in higher states of oxidation. Since most observations concerning manganiferous sediments have been made at or near the surface where the effects of weathering are widespread, many investigators appear to have been led unconsciously to assume an

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des Leipziger Mitteloligocäns und die norddeutschen Phosphoritzonen, Abh. k. Sachs. Gesell. Wiss., Bd. 22, 1895, pp. 1–47; Davies, D. C., On a bed of phosphate of lime, northwest of Llanfyllin, North Wales, Geol. Mag., vol. 4, 1867, p. 257; Dugast, L., Les phosphates d'Algérie, Rev. Gén. des Sci. Pures et Appliquées, vol. 8, 1897, pp. 769–782; Elschener, C., Corallogene Phosphat-Inseln Austral-Oceaniens und ihre Producte, 1913; Fuchs, E., et de Launay, L., Traité des gîtes min. et mét., 1893; Lacroix, A., Minéralogie de la France, vol. 4, 1910, pp. 555–600; Matson, G. C., The phosphate deposits of Florida, Bull. 604, U. S. Geol. Surv., 1915; Matthew, W. D., On phosphatic nodules from the Cambrian of southern New Brunswick, Trans. New York Acad. Sci., vol. 12, 1893, pp. 108–120; Murray, J., and Philippi, E., Wiss. Ergebn. der deutschen tiefsee Exped., 10, Lief. 4, Jena, 1908; Penrose, R. A. F. jr., Nature and origin of deposits of phosphate of lime, Bull. 46, U. S. Geol. Surv., 1888; Reese, C. L., On the influence of swamp waters in the formation of phosphatic nodules of South Carolina, Am. Jour. Sci., vol. 43, 1892, p. 402; Richards, R. W., and Mansfield, G. R., Phosphate deposits of Georgetown, Idaho, Bull. 577, U. S. Geol. Surv., 1914; Rogers, A. F., Collophane, a much neglected mineral, Am. Jour. Sci., vol. 3, 1922, pp. 269–276; Sellards, E. H., Ann. Rept. Florida Geol. Surv., 1913; Shaler, N. S., On the phosphate beds of South Carolina, U. S. Coast Surv. Rept. for 1870, pp. 182–189; Smith, E. A., The phosphates and marls of the State, Report on the Geology of the Coastal Plain of Alabama, 1894, pp. 449–525; Stutzer, O., Lagerstätten der Nichterze, Berlin, 1911; Teall, J. J. H., Summary of phosphate deposits, Proc. Geologists' Assoc., vol. 16, 1900, p. 369; Thomas, P., Giséments des phosphates de chaux des hauts plateaux de Tunisie, Bull. Soc. Géol. France, vol. 19, 1891, p. 370.

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abundance and wider distribution of manganese oxides than may be justified. In recent years, it has become quite certain that manganiferous carbonates are much more widespread in unweathered sediments than the oxides.

MANGANESE IN IGNEOUS ROCKS, WATERS, AND ORGANISMS

Among 135 specimens of a wide variety of igneous rocks that are assuredly not metamorphosed,[892] manganous oxide attains a maximum of 0.93 per cent in a hypersthene gabbro from Minnesota. In most rocks, the percentage ranges from 0.05 to 0.15. In general, the percentage is highest in the basic rocks rich in iron and lowest in the alkaline rocks. There is little, however, to indicate that the chemical character of the rocks which surround a basin of sedimentation is an important factor in determining the degree of concentration of manganese in the nearby sediments.

Although there is an abundant record of the manganese content of river waters, especially in Europe and North America where its deposition in city supply systems has been cause for concern, there is surprisingly meagre record of the amount present in waters from hot and cold springs, lakes, and the seas. In a broad way, the manganese content attains its maximum of about 117 parts per million in certain spring waters; it commonly ranges from 0.5 to 5 parts per million in river waters in the temperate zone, and while the amount in sea water has not yet been accurately determined, it is assuredly much less than the amounts recorded in springs and rivers. One may readily conclude from existing data that in the progress of water from the sources of rivers to the seas, manganese oxide is steadily removed from solution, although it is not definitely known whether the precipitation is caused by organisms or by simple chemical reactions. In general, waters that contain much manganese belong to the mixed carbonate type and it has been widely asserted that manganese is transported in solution as the bicarbonate. As the chemistry of manganese has many resemblances to that of iron, it seems probable that manganese, like iron, is not carried as bicarbonate in natural surface solutions high in organic matter as has been widely assumed, but in all probability it is transported as manganese oxide hydrosol, stabilized by organic colloids.[893]

Manganese seems to be present in most if not all living organisms, both animal and plant, but it is not known that any but the lowest organisms, such as bacteria and algæ, play an important part in determining the amount of manganese in sediments. Many manganiferous sediments contain

[892] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 437–473.

[893] Moore, E. S., and Maynard, J. E., Solution, transportation and precipitation of iron and silica, Econ. Geol., vol. 24, 1929, pp. 272–303; 365–402; 506–527.

marine invertebrate fossils, but even where they are present there is no apparent relation between the quantity of manganese and the number of organisms.

Probably bacteria and algæ deserve most serious consideration as active agents in precipitating manganese from solution.[894] As a result of considerable experimental work, it seems clear that several genera of bacteria common in soils and in oceanic muds, especially *Crenothrix*, *Leptothrix*, *Cladothrix*, and *Clanothrix*, precipitate manganese oxides from a number of manganese salts. It is also possible but not yet demonstrated that some bacteria precipitate manganese carbonate. As to the extent to which manganese bacteria have played a part in depositing known deposits of manganese oxides and carbonates, opinions differ widely. Vernadsky[895] asserts that bacteria are largely responsible for the change from manganous compounds to the higher manganese oxides and doubts that free atmospheric oxygen can oxidize such compounds at ordinary temperatures. This is obviously an extreme position and ignores much laboratory work that has been done. Some students of the work of algæ in depositing calcium carbonate look with favor upon the possibility that the spherical and concretionary forms of manganese oxides, such as those found in the beds of manganese oxide near Tschiaturi, Russia, may have been deposited by algæ.[896] It has been found that certain algæ abstract manganese oxides from the waters of the Elbe Valley which contain 0.25 to 0.65 parts per million and the fact has been the basis of processes to remove manganese from the waters.[897] Recent studies by D.

[894] It has been known for about 100 years that certain bacteria selectively precipitate iron oxides from solution, and nearly as long that similar organisms precipitate manganese oxides. Consequently there is abundant literature on the subject, especially in German, Swedish, and French. The literature is well summarized by W. Vernadsky, in "La Géochimie," Paris, 1924, in which there is a chapter entitled "Histoire géochimique du manganèse," pp. 74–110. More important recent publications follow: Beijerinck, M. W., Oxidation of manganese carbonate by bacteria and fungi, Fol. Mikrobiol., 2, no. 2, 1913, Summarized in Zentr. Biochem. Biophys., vol. 16, 1913–1914, p. 277; Söhngen, M. L., Umwandlungen von Manganverbindungen unter dem Einfluss mikrobiologischer Prozesse, Zentr. f. Bakteriologie, Abt. ii, vol. 40, 1914, pp. 545–554; Naumann, E., Ueber die See- und Sumpferze von Süd- und Mittel-Schwedens (Swedish with German review), Sver. Geol. Undersökning, Årsbok 13, 1922; Thiel, G. A., Manganese precipitated by microorganisms, Econ. Geol., vol. 20, 1925, pp. 301–311; Perfiliew, B. W., Die Rolle der Mikroben in der Erzbildung, Verhandl. Intern. Ver. f. Limnologie, vol. 3, 1927; Butkevich, E. S., The formation of marine iron and manganese deposits and the rôle of microorganisms in the latter, Wiss. Meeresinst., Berlin, 3 (3), 1928, pp. 7–80; Zapffe, C., Deposition of manganese, Econ. Geol., vol. 26, 1931, pp. 799–832. This article contains an excellent bibliography.

[895] Op. cit., pp. 98–99.

[896] White, David, personal communication.

[897] Vollmer, D., Die Entmangung des Grundwassers in Elbethal und die für Dresden ausgeführte Anlagen, Jour. Gasbel., vol. 57, 1914, pp. 956–959.

White of calcareous tufa deposited by algæ near Furnace Creek, West Virginia, indicate that in times of drought such algæ also deposit manganese oxide.[898]

MANGANESE IN SEDIMENTARY ROCKS

Manganese in Clastic and Carbonate Sediments

Sandstones and the coarser sediments ordinarily contain little manganese, and that little is commonly confined to the undecomposed fragments of the source rocks or minerals. Analyses show quantities that range from mere traces to about 1.5 per cent manganese oxide.

Glauconitic sands appear to contain little manganese but, curiously, beds of these sands not infrequently occur near beds of manganiferous carbonate. Similarly, phosphatic oolites contain little manganese but in several localities they occur near manganiferous sediments. The beds of oolitic and fossil hematite which have been laid down in a manner similar to coarse sediments uniformly contain a little manganese, the percentage ranging from 0.2 to 0.5. Greenalite contains little manganese.

Small quantities of manganese oxides are present in most fresh specimens of shales and slates. Analyses show a range from a trace to 5.87 per cent. The quantity rarely exceeds one per cent and the range is commonly from 0.05 to 0.30 per cent, amounts not differing greatly from the content in the original igneous rocks. The percentage in the black and green slates appears to be higher than in those that are red and gray. Although the manganese content of fine sediments is rather uniformly low, zones of such sediments in many places contain thin layers of carbonate minerals which are locally rich in manganese. In these places, the percentage of manganese appears to be related to the content of ferrous iron.

There are comparatively few good determinations of manganese in the carbonate rocks. Pure non-magnesian limestones rarely contain more than 0.1 per cent of manganese oxide and similar quantities are present in fresh-water marls, travertines and tufas. On the other hand, the magnesian limestones commonly contain more manganese and the quantity tends to increase with the content of ferrous carbonate. Carbonate rocks with less than one per cent ferrous oxide commonly contain less than 0.1 per cent of manganese oxide but where the ferrous oxide content exceeds 20 per cent, that of manganese oxide rarely is less than 0.7 per cent.

[898] Howe, M. A., The geologic importance of the lime-secreting algae, Prof. Paper 170, U.S. Geol. Surv. (in preparation).

Manganese Oxides in Sediments

Among the beds of pure manganese oxides interlaid with coarse sediments, none are more important than those of the Caucasus region of Russia.[899] These have been extensively explored near Tschiaturi where in a single bed in an area of 130 square kilometers there are estimated to exist from 100 to 150 million tons of marketable manganese ore. This bed lies in marly sand transitional from the Eocene to the Oligocene. Similar beds at a similar horizon are recorded sporadically in an area about 90 kilometers in diameter. Similar deposits are recorded in Oligocene beds in the Nikopol district, Russia, and in Pliocene beds on the Island of Milos, Greece.

In the Tschiaturi district, the manganese oxides form oolites that make up a large part of distinct lenses in medium-grained arkosic sandstones. In the explored region, the thickness of the bed ranges from 6 to 14 feet but the thickness of the separate lenses of manganese oxides ranges from 3 to 24 inches. Commonly, the aggregate thickness of these lenses is less than half the thickness of the bed. The oolites appear to be psilomelane and pyrolusite and are largely flat ellipsoids whose larger diameters range from 1 to 10 mm. and average about 3 mm. (figs. 67–68). Most of these oolites contain a nuclear grain of quartz or feldspar but little more foreign material. Some are angular and appear to be broken fragments of symmetrical oolites. The oolites are imbedded in a matrix of arkosic material, the grains of which, quartz, feldspars, and mica, largely range from 0.05 to 0.10 mm. in diameter. The cement is calcium carbonate. Numerous perfect shark teeth and a few invertebrate fossils indicate a marine origin for the beds. As the oolites are rudely sorted into distinct layers and some are broken, it seems that the oolites were formed in another habitat and have been transported to their present site. Furthermore, most oolites have shrunken away from their matrix and it seems that they must have steadily lost water since they were formed in their original habitat. De la Sauce does not think that the oolites have an organic origin.

Some of the manganese deposits of Oriente Province, Cuba, closely resemble those of the Tschiaturi region, especially those at the Sultana, Isabelita, and Cauto mines near Cristo.[900] Beds of tuffaceous material in lower Eocene rocks contain disseminated round grains of manganese oxide

[899] Drake, F., The manganese ore mining industry of the Caucasus, Trans. Am. Inst. Min. and Met., vol. 28, 1898, pp. 191–208; Zeretelle, D., Manganese ore with special reference to Georgian ore, Dryden Press, London, 1925, p. 136; De la Sauce, W., Beiträge zur Kenntniss der Manganerzlagerstätte Tschiaturi in Kaukasus, Abhandl. zur prak. Geol., Halle, 1926, 87 pp. and 3 maps. Contains bibliography of 40 titles.

[900] Burchard, E. F., Manganese ore deposits of Cuba, Trans. Am. Inst. Min. Eng., vol. 63, 1919, pp. 67–75.

FIG. 67. A POLISHED SURFACE OF LOW-GRADE MANGANESE OXIDE ORE FROM THE TSCHIATURI DISTRICT, RUSSIA

The oolites are pyrolusite; the light matrix is composed of grains of quartz, feldspar, and mica in calcite. Secondary pyrolusite has replaced the matrix in the dark area. The scale indicates inches.

as much as 6 mm. in diameter. The manganese content of beds as much as 20 feet thick ranges from 10 to 20 per cent. Some beds contain considerable glauconite. At the Charco Redondo mine, there is a bed about 15 inches thick made up of nearly pure manganese oxide in the form of small cauliflower-like growths which suggest the forms of algæ.

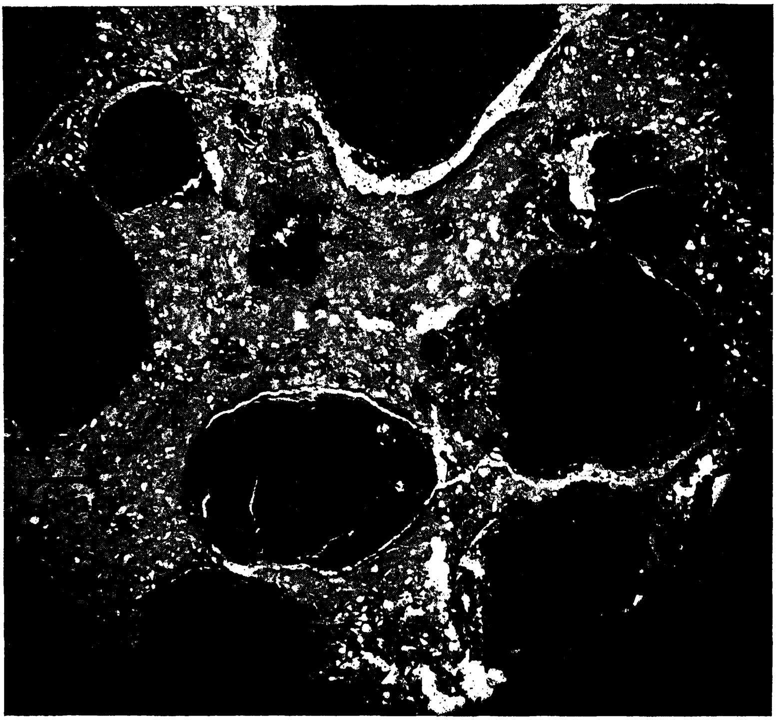

FIG. 68. MICROPHOTOGRAPH OF SOME MATERIAL SHOWN IN FIGURE 67
Note shrinkage cracks filled with calcite. Ten times natural size

Near Las Vegas, Nevada,[901] there are several beds of nearly pure wad as much as 36 feet thick included in latite tuffs of Pliocene age. Also near Cleveland, Idaho,[902] beds of nearly pure wad are found in fine sands and clays laid down on the shore of a Pleistocene lake. Near Artillery Peak and Topock, Mojave County, Arizona,[903] wad impregnates latite tuff and ar-

[901] Hewett, D. F., and Webber, B. N., Bedded deposits of manganese oxides near Las Vegas, Nevada, Bull. Univ. Nevada, vol. 25, no. 6, 1931, p. 17.

[902] Hewett, D. F., A manganese deposit of Pleistocene age in Bannock County, Idaho, Bull. 795, U. S. Geol. Surv., 1928, pp. 211–221.

[903] Jones, E. L., and Ransome, F. L., Deposits of manganese in Arizona, Bull. 710–D,

kosic sandstone that occur in a group of tuffs and sandstone of mid-Tertiary age. The source of the manganese in these occurrences in Idaho, Nevada, and Arizona seems to be nearby hot springs and there is no evidence that organisms have caused deposition of the oxides.

In India and Brazil,[904] manganese deposits are widespread. In both countries there are outstanding deposits of manganese silicates, now weathered to oxides, in ancient gneisses and crystalline rocks, and in the same general regions, younger but pre-Paleozoic rocks contain stratified bodies of manganese oxides locally altered to silicates. In India, the beds of manganese oxides are associated with quartzites and limestones of the Dharwar series, and in the Miguel Burnier and Ouro Prieto districts, Brazil, such beds are associated with quartzites of the Piracicaba and Itabira formations. Since the oxides have been recrystallized, their original relations are obscure.

Manganese Carbonates in Sediments

To an increasing degree in recent years, data have been collected which show that thin zones of manganiferous carbonates and carbonate concretions are fairly common in fine-grained marine sediments. Although some accounts of such zones state that manganese oxides also accompany the carbonates, it is not yet certain that such oxides are not the product of recent weathering. Recalculation of analyses of material from several localities (Newfoundland, Wales) indicates the presence of rhodonite, the metasilicate of manganese. It seems probable that this mineral has formed during the process of incipient metamorphism after burial.

Near Trinity and Conception bays, Newfoundland,[905] a section made up largely of thin-bedded red and green shales contains thin layers of green jaspery carbonate of manganese as well as layers of calcium phosphate and baritic concretions. In the section on Manuels River there are four persistent and several lenticular layers of such carbonates which range from 0.2 to 0.7 feet thick. In the Brigus section, six beds with a total thickness of 4.5 feet contain appreciable manganese. Most of the manganese is present

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U. S. Geol. Surv., 1920, pp. 143–149, 153–159; Wilson, E. D., and Butler, G. M., Manganese ore deposits of Arizona, Bull. 127, Univ. of Arizona, 1930, pp. 71–81.

[904] Fermor, L. L., Manganese ore deposits of India, Mem. Geol. Survey of India, vol. 37, 1909, p. 1294; Harder, E. C., Manganese ores of Russia, India, Brazil, and Chile, Bull. Am. Inst. Min. Eng., 1916, pp. 761–798.

[905] Dale, N. C., Cambrian manganese deposits of Conception and Trinity Bays, Newfoundland, Proc. Am. Philos. Soc., vol. 54, 1915, pp. 378–449. This article has an excellent bibliography.

as manganese carbonate, the content of which ranges from 10.23 to 44.39 per cent. In addition, the manganese dioxide content ranges from 2.34 to 28.93 per cent. Nearby, on Placentia Bay,[906] somewhat similar beds include a layer which contains 84.6 per cent manganese carbonate.

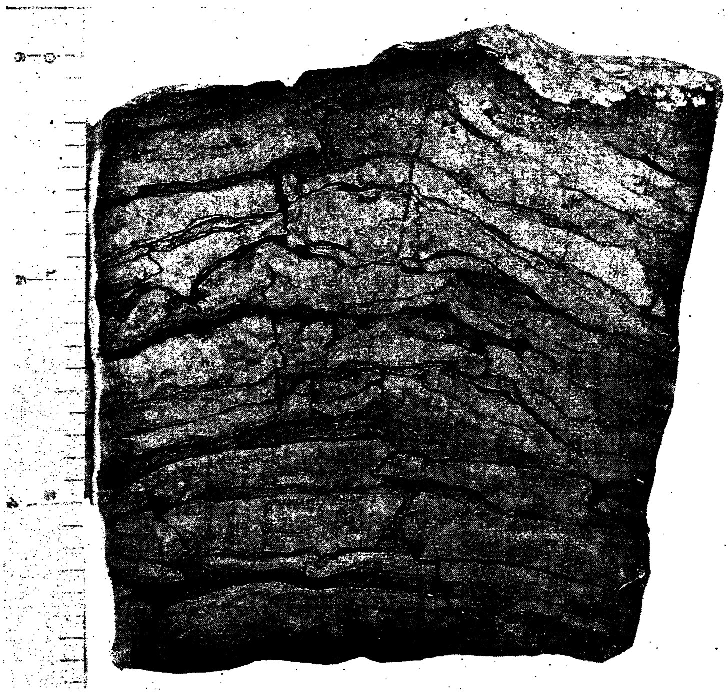


FIG. 69. THINLY LAMINATED HIGH-GRADE MANGANESE CARBONATE
This sample is from a bed interlayered with Franciscan Chert (Jurassic), Buckeye Mine, San Joaquin County, California. The scale indicates inches.

Similar beds of rather pure manganese carbonate are recorded in Cambrian grits and shales in Merionethshire,[907] Wales, and near Chevron, Belgium.[908] In the latter locality, the bed of carbonate, 3.9 feet thick, is associated with layers of jasper; selected specimens contain as much as 84 per cent $MnCO_3$.

[906] Hunt, T. S., Geol. Surv. Canada, 1857–58, pp. 204–205.

[907] Halse, E., The occurrence of manganese ore in the Cambrian rocks of Merionethshire, Trans. N. Eng. Inst. Min. Eng., vol. 36, 1887, p. 103.

[908] DeWalque, G., Sur le rhodochrosite de Chevrons, Ann. Soc. Géol. de Belgique, vol. 11, 1883–1884, pp. lxiii–lxv.

Explorations of the manganese deposits that occur widely in the Franciscan (Jurassic) cherts of California have recently shown the presence of thinly laminated beds of gray, nearly pure manganese carbonate (see fig.

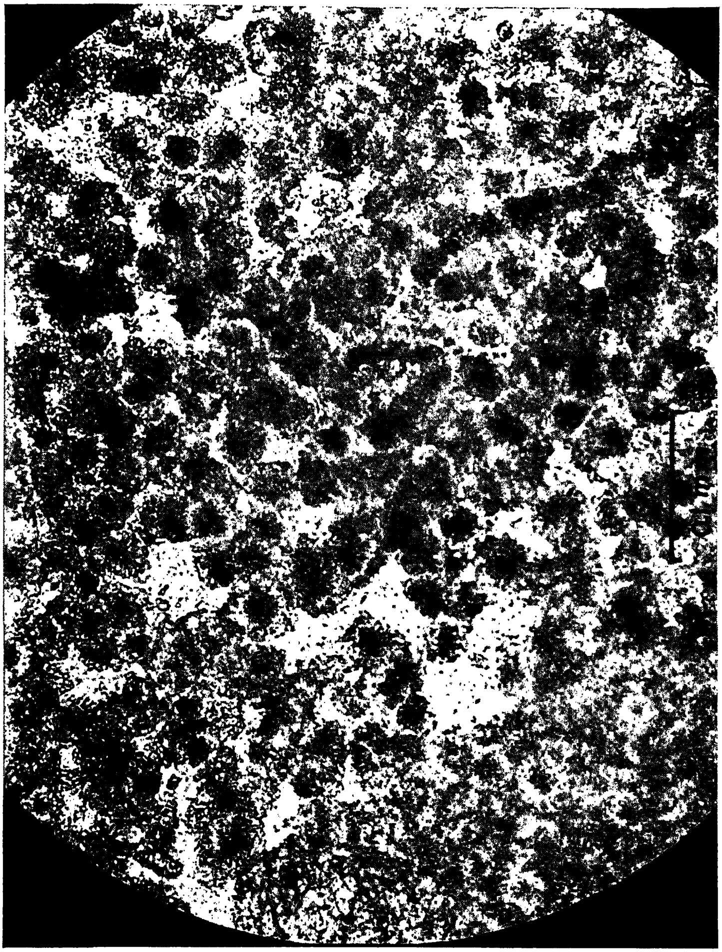


FIG. 70. MICROPHOTOGRAPH OF SOME MATERIAL SHOWN IN FIGURE 69
The manganese carbonate forms minute oolites. Magnified 200 diameters

69) from 2 to 6 feet thick. The separate laminæ range from 0.1 to 0.2 inch thick and are made up of minute spherules (figs. 69–70). Thin sections show sporadic foraminiferal remains. Near intrusive rocks such beds are

altered to hausmannite, hydrous manganese silicates (neotocite and bementite), and pink rhodochrosite.[909] The enclosing rocks, the thin-bedded cherts that make up the Franciscan formation, have been studied by Davis.[910]

In the Batesville district,[911] Arkansas, the Cason shale of Upper Ordovician age attains a maximum thickness of 12 feet. It is largely made up of thin, rather persistent layers of shale, fine sandstone, phosphate and nodules of iron-manganese carbonate. It overlies unconformably the Fernvale limestone which persistently contains small percentages of manganese, and is generally overlain unconformably by the St. Clair limestone. The nodules of iron manganese carbonate resemble concretions but are regarded by Ulrich as fossil algæ of the genus *Girvanella*. The unweathered nodules are pale greenish gray and the manganese is entirely in the form of carbonate. Where mined under cover and unoxidized, the nodular layers, 3 to 8 feet thick, contain from 12 to 20 per cent manganese and 7 to 10 per cent iron.

Numerous mines on the Cuyuna Range, Minnesota,[912] explored below the oxidized ores, encounter cherty, manganese-bearing iron carbonate interlayered with shales and amphibolite rocks. Such carbonate rocks contain as much as 30 per cent iron and 5 per cent manganese which are largely, if not wholly, present as carbonates. These rocks are a part of the Deerwood iron-bearing member of the Virginia slate, probably of upper Huronian age.

An interesting zone of manganese-iron carbonate concretions has recently been explored near Chamberlain, South Dakota. The zone of shale, 38 feet thick, lies 130 feet above the base of the Pierre shale (Upper Cretaceous) and 6 feet above a persistent sandstone layer. The nodules are flattened spheroids 3 to 8 inches in diameter, commonly show nuclei of shells (*Inoceramus*) and fragments of bones, and contain about 16 per cent manganese and 10 per cent iron. They are not uniformly distributed through the 38-foot bed but are concentrated in narrow persistent layers. Exhaustive tests indicate that 12 cubic yards of shale yield one ton of nodules. Close study of the nodules shows that the ratio of manganese to iron is twice as great in the center as in the peripheral zone. Furthermore, on exposure to weathering, the iron tends to oxidize in advance of the manganese. From these relations, it appears that when the nodules were forming, manganese

[909] The writer's observations.

[910] Davis, E. F., The radiolarian cherts of the Franciscan group, Univ. California, Dept. Geol. Publ., vol. 11, 1918, pp. 235–432.

[911] Miser, H. D., Deposits of manganese ore in the Batesville district, Arkansas, Bull. 734, U. S. Geol. Surv., 1922, pp. 23–28.

[912] Harder, E. C., and Johnston, A. W., Geology of east central Minnesota, Bull. 15, Minnesota Geol. Surv., 1918, p. 168.

which probably existed in the sediment as an oxide was more readily susceptible to reduction than iron. The relations confirm the theory announced many years ago by Dieulafait.[913]

In several parts of the eastern United States, bodies of manganese oxides in residual materials occur persistently over large areas at definite stratigraphic horizons in such a way as to indicate that the oxides are derived from nearby sources. Explorations to depths that commonly range from 200 to 400 feet below the nearby surface yield only the oxides similar to those near the surface but have not yet revealed the materials from which they may be derived. Such horizons are formed in Pre-Cambrian rocks in the Piedmont region from Lynchburg, Virginia, to Abbeville, South Carolina;[914] at the base of the Shady dolomite (Lower Cambrian) from southwestern Virginia to northeastern Alabama;[915] at the contact of the Holston marble with the Tellico sandstone (Lower Ordovician) of east Tennessee;[916] at the base of the Oriskany sandstone (Lower Devonian) in western Virginia;[917] and in the Fort Payne chert (Mississippian) of eastern Tennessee and northern Alabama.[918] The outcrops of two of these zones, the Shady and Oriskany, contain iron as well as manganese deposits but the other three yield only manganese. The manganese deposits at the lower two of these five zones, the Pre-Cambrian and Shady, occur in the transition zone from sandstones to limestones; the third lies largely in limestone near its contact with overlying sandstone; the fourth lies in shale and chert beds at the base of the Oriskany sandstone where it unconformably overlies limestone; and the fifth zone (Fort Payne) lies wholly in thin-bedded chert, much like the beds of manganese carbonate in the Franciscan cherts of California. For each of these areas, the conclusion is reached that the unweathered materials or sources of the manganese oxides are stratified layers of either rather pure manganese carbonate or concretionary zones of iron-manganese carbonate with little or no oxide. The conclusion is based upon the general lithologic resemblances to sections that contain carbonate layers in contrast with those which contain layers of oxides.

[913] Dieulafait, L., Application des lois de la thermochimie aux phénomènes géologiques; minérais de manganèse, Compt. Rend. Acad. Sci., Paris, vol. 101, 1885, pp. 609, 644, 676.

[914] Harder, E. C., Manganese deposits of the United States, Bull. 427, U. S. Geol. Surv., 1910, pp 37–46.

[915] Stose, G. W., et al, Manganese deposits of the west foot of the Blue Ridge, Virginia, Bull. 17, Virginia Geol. Surv., 1919, p. 166; Hull, J. P. D., La Forge, L., and Crane, W. R., Manganese deposits of Georgia, Bull. 35, Geol. Surv. of Georgia, 1919, p. 295.

[916] Stose, G. W., and Schrader, F. C., Manganese deposits of east Tennessee, Bull. 737, U. S. Geol. Surv., 1923, pp. 29–31.

[917] Stose, G. W., and Miser, H. D., Manganese deposits of western Virginia, Bull. 23, Virginia Geol. Surv., 1922, p. 206.

[918] Stose, G. W., and Schrader, F. C., op. cit., p. 31.

The recent discovery of hauerite (bisulphide of manganese) in the cap rock of two salt domes in Matagorda and Galveston counties, Texas, is interesting.[919] It is associated with anhydrite and probably represents a rearrangement of the manganese and sulphur present in the sediments rather than an original constituent.

Manganese in Deep-sea Deposits

According to Murray and Renard, hydrates and oxides of manganese are among the most widely distributed substances in marine deposits. These occur as (a) finely divided coloring matter in some deep-sea sediments; (b) coatings over shells, bones, teeth, fragments of rock, etc.; and (c) nodules and concretions.

Some manganese is present in nearly every sample of deep-sea sediments. Deep-sea clays are probably decomposition products of pumice, volcanic glass, windblown dust, and other fine particles, and their reddish brown color is due to the presence of oxides of iron and manganese. In some shallow places, such as the Clyde Sea,[920] the surface layer of the muds is reddish whereas the underlying material is blue. The exposed surfaces of rocks that rest upon the bottom are covered with manganese oxide but the parts embedded in the mud are not coated.

In a broad way, the sediments of the ocean basins that are surrounded by basic rocks have a higher content of manganese than those surrounded by other types. Thus, in general, a given area of the bottom of the Pacific Ocean contains more manganese oxide nodules than an equal area of the bottom under the Indian Ocean and much more than an equal area of the bottom under the Atlantic. Similarly, the red clays of the Pacific are darker and contain more manganese than those of the Indian Ocean, which in turn are darker than those of the Atlantic.

Manganese oxide nodules occur sporadically in all of the ocean basins. In shape, the nodules range from spherical and elliptical to irregular; the surfaces are commonly botryoidal or mammillary, much like those which characterize residual deposits. To a considerable extent, the shapes appear to depend upon the shapes of the nuclei which commonly are fragments of pumice or volcanic rock. Such nuclei are greatly altered and more or less replaced by manganese oxide. It is stated that the nodules of each locality

[919] Wolf, A. G., Hauerite in a salt-dome cap rock, Bull. Am. Assoc. Pet. Geol., vol. 10, 1926, pp. 531–532; Hanna, M. A., A second record of hauerite associated with Gulf Coast salt domes, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929.

[920] Murray, J., and Irvine, R., On the chemical changes which take place in the composition of sea water associated with blue muds on the floor of the ocean, Trans. Roy. Soc. Edinburgh, vol. 37, 1893, pp. 431–508; On manganese oxide and manganese nodules in marine deposits, Ibid., vol. 38, 1894, pp. 721–742.

tend to have similar shapes and sizes. Nodules as much as 15 cm. in diameter have been recovered but the fragments dredged by the "Challenger" show that larger masses are present.

Typical analyses of some nodules are shown in table 85. Commonly, manganese oxide equals or exceeds iron oxide and these make up about 60 per cent of the weight. In the nodules from the ocean deeps, the manganese is largely in the state of MnO_2 but in those from littoral zones, it is largely Mn_2O_3; in both, the kernels are more highly oxidized than the surface layers.

Most of the information concerning manganese nodules here presented has been derived from the works listed below.[921]

TABLE 85

	1	2	3	4
SiO_2	6.00	18.97	28.30	15.00
Al_2O_3	3.50	2.45	3.25	2.00
Fe_2O_3	32.90	19.58	23.08	22.00
MnO_2	25.64	32.48	29.09	30.00
$CaCO_3$	3.15	3.07	2.58	3.00
$CaSO_4$	1.16	0.58	0.62	0.70
$Ca_3P_2O_8$	0.90	0.20	Trace	Trace
$MgCO_3$	1.51	1.72	3.40	1.50
Insoluble CaO and MgO	0.40	0.55	0.78	
Loss on ignition	24.84	20.40	8.90	15.00
	100.00	100.00	100.00	

1. Depth 1525 fathoms, southwest of Canary Islands.
2. Depth 2600 fathoms, southwest of Australia.
3. 3000 fathoms, south of Hawaiian Islands.
4. Approximate average of 40 analyses.

Recently it has been determined[922] that deep-sea nodules as well as those from streams are more radioactive than the average igneous and sedimentary rocks.

Nodules of manganese oxide are not uncommon in fresh-water lakes. In

[921] Buchanan, J. Y., On the composition of oceanic and littoral manganese nodules, Trans. Roy. Soc. Edinburgh, vol. 36, 1892, pp. 459–483; Murray, J. and Renard, A. F., Deep sea deposits, Challenger Rept., 1891; Murray, J. and Hjort, J., Depths of the ocean, 1912, pp. 149–190; Molengraaf, G. A. F., Manganese concretions in Mesozoic deep sea deposits of Borneo, Timor, and Rotti, Verslag, K. Akad. Wetensschappen, Amsterdam, vol. 23, 1915, pp. 1058–1073; Collet, L. W., Manganese in sediments, in Les dépôts marins, Paris, 1908.

[922] Iimori, S., Formation of the radioactive manganiferous deposits of Tanokami, Bull. Chem. Soc. Japan, vol. 2, 1927, pp. 270–273.

Lock Tyne of Scotland[923] the nodules have been found and in Zeller Sea, Austria,[924] nodules as much as 8 inches in diameter having the composition of those of the deep sea have been dredged from water about 20 meters deep.

STRATIGRAPHIC RELATIONS OF MANGANIFEROUS SEDIMENTS

The stratified rocks with which the bedded manganese oxides are associated show a wide range in lithology: limestones, marls, tuffs of diverse kinds, shales, and sandstones. Many recent bog deposits are as yet uncovered by other sediments.

On the other hand, certain lithologic associations are characteristic of the stratified manganese carbonates. First, they are commonly associated with beds of chert, glauconite, and calcium phosphate. Next, this assemblage of materials is commonly found in the fine-grained sediments, generally where they are transitional from coarse sandstones to massive limestones.

Not only do the manganiferous carbonates contain much more phosphoric acid than most sediments, but distinct beds of these carbonates and phosphatic nodules occur in close proximity, locally thick enough to be mined. This association is noteworthy in Arkansas (Ordovician), Virginia (Oriskany), and Newfoundland (Cambrian). Beds of chert are common near manganiferous carbonates in California (Calaveras and Franciscan formations) and in Oregon, in Minnesota (Cuyuna Range), in Tennessee and Alabama (Fort Payne chert), in western Virginia (Oriskany), in western Arkansas (novaculite), and Newfoundland. Chert is an accessory mineral in the manganese district of Grande County, Utah, and at the base of the Shady dolomite in the Appalachian region. On the other hand, little or no chert is known in the Batesville district (Arkansas), and in the many regions in New York, Pennsylvania, Maryland, Kentucky, Ohio, and South Dakota where manganiferous siderites are known. The associations suggest that the conditions which favor the deposition of beds of phosphate, chert, and glauconite also favor the deposition of manganiferous carbonates. Crystals of barite, apparently formed soon after the sediments were laid down, are common in Arkansas and Newfoundland.

In the second place, a relation between manganiferous carbonates and unconformities is suggested. In western Virginia, the manganiferous zone (carbonate?) overlies the first bed of sandstone of the Oriskany where it unconformably overlies the Helderberg limestone. In the Batesville district, the manganiferous Cason shale unconformably overlies the Fernvale

[923] Buchanan, J. Y., Proc. Roy. Soc. Edinburgh, vol. 8, 1890, p. 19.

[924] Lasch, H., Concretions of manganese ore from Zeller Sea, Tscher. Min. Pet. Mitt., vol. 40, 1930, pp. 294–296.

limestone. In the Blue Ridge region of Virginia, the manganese (carbonate?) bearing beds lie over a Lower Cambrian quartzite. The manganiferous carbonate of Newfoundland occurs in green and red shales that lie 100 feet or more above the basal Cambrian conglomerate. Such relations are recorded in Belgium, Germany, and Austria. On the other hand, the manganiferous iron carbonates of the "Coal Measures" of Pennsylvania, Ohio, and Kentucky and in the Cretaceous rocks of South Dakota have no recognized relation to unconformities.

SITES OF DEPOSITION OF MANGANESE DEPOSITS

If the beds of iron oxide which contain a little manganese (0.10 to 0.20 per cent) such as are found in the Clinton formation, be ignored, there is no convincing evidence that beds of manganese oxide have been deposited in North America during the Paleozoic or Mesozoic eras. Such beds are known in Tertiary and Quaternary rocks in both North America and Europe. The bedded oxides of Brazil and India are Pre-Cambrian. In some places the beds occur in marine strata (Tschiaturi, Nikopol, and Cuba); some are clearly interbedded with terrestrial deposits (Arizona, Nevada, Idaho) and the source of the manganese here appears to be nearby hot springs.

Beds of manganiferous carbonates commonly occur with strata which appear to have a marine origin. The associated strata, however, are not characterized by an abundance of fossils. In age they range from Pre-Cambrian to late Mesozoic. There is a meagre record that carbonates have been deposited in modern bogs. It is not always clear, however, whether the marine carbonates were deposited as such, or whether the contained manganese was deposited as oxides in sediments that contained organic matter and was later reduced and converted to the carbonate before being deeply buried. The beds of pure manganese carbonate (Franciscan formation) were probably deposited as such. On the other hand, most beds of impure carbonates are concretionary and bear evidence of solution and redeposition of the manganese (South Dakota).

Bedded manganiferous carbonates appear to have three types of stratigraphic relations, suggesting as many different environments: (1) In most places, they occur in fine-grained sediments which overlie coarser sediments which in turn rest on a surface of unconformity. Commonly they contain organic matter, fossil remnants, and a little pyrite. Under these conditions they appear to form part of the fine marine sediments laid down near the shores of shallow seas. (2) They occur in the alternating thin beds of coarse and fine sediments and marine limestones such as are common in the "Coal Measures" of the Appalachian region. In such places iron greatly exceeds manganese in the carbonates. (3) They occur in thin-bedded marine

cherts with minor shale and limestone. Such carbonates rarely contain iron. They do not appear to be deposited in the midst of thick limestone sections, or in coarse sediments.

PROCESSES LEADING TO THE DEPOSITION OF MANGANESE MINERALS

Although it is known that manganese is rapidly removed from solution during the progress of surface waters from their sources in springs through small streams and rivers to the seas, little is known with assurance concerning the processes by which manganese accumulates in quantities above the average in sediments, either as oxides or carbonates. As in the case of iron, whose chemistry resembles that of manganese, there is no good evidence that excessive accumulations of either element in sedimentary deposits depend in any appreciable degree upon excessive percentages in the rocks that surround the basins in which the waters rise. The average igneous rock[925] contains 5.08 per cent iron and 0.125 per cent manganese, so that the ratio is about 40 to 1. Where there are sediments that are appreciably rich in either of these elements, the ratio of the two is generally widely different. Especially is this true in the case of the oxide-bearing sediments; many iron carbonate zones contain these elements in the ratio of about 40 to 1.[926]

To approach a satisfactory explanation of the accumulation of sedimentary zones of rich manganese oxides or carbonates, it seems necessary to explain (1) the earlier selective elimination of iron from the waters; (2) the selective deposition of the manganese minerals; and (3) the extraordinary local increase in manganese in thin stratigraphic zones. Experiments in the laboratory indicate that under several circumstances iron oxides tend to deposit more readily than, and therefore before, manganese oxides. Probably organisms play a large part in the early precipitation of iron as well as in the later selective precipitation of manganese, although some bacteria will precipitate either which may be available. No adequate explanation has yet been offered to account for such extraordinary local concentrations of pure manganese oxides as are known in the Caucasus region of Russia or of those of manganese carbonate in the Franciscan formation of California. They may be due to organisms but as yet nothing is known concerning the habitat under which the latter thrive.

SECONDARY MANGANESE DEPOSITS

Some of the oxides of manganese, especially pyrolusite and psilomelane, are highly stable in the zone of weathering under most climatic conditions,

[925] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1929, p. 29.

[926] Penrose, R. A. F., jr., The chemical relations of iron and manganese in sedimentary rocks, Jour. Geol., vol. 1, 1893, pp. 356–370.

but most of the other manganese minerals are readily susceptible of solution. The common sulphides, carbonates, silicates, and phosphates are quickly oxidized under most conditions, especially those minerals in which manganese exists in the lowest state of oxidation. Although the presence of the bicarbonate probably has not been definitely proved in any natural

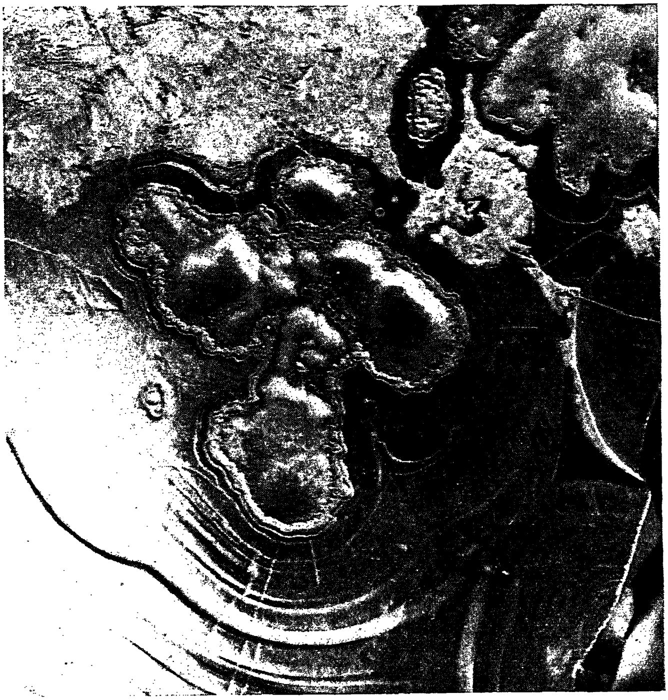


FIG. 71. POLISHED SURFACE OF CONCENTRICALLY BANDED DENSE PSILOMELANE AND ASSOCIATED CRYSTALLINE MANGANITE

Consists of soft structureless cores of pyrolusite or wad surrounded by banded psilomelane, the inner layers of which are highly crinkled and in cavities and crevices of which there is crystalline manganite (shown in upper left corner). From Cook Mine, near Walnut Grove, Alabama. Three times natural size. Photograph contributed by G. W. Stose, U. S. Geol. Surv.

waters, it has generally been assumed that manganese in solution exists in that combination. From recent work on the transport of iron in solution, it would appear that the manganese in waters that carry organic matter exists in the state of the hydrosol, stabilized by organic colloids. The first precipitate from solution seems to be flocculent hydrous oxide similar to wad and, in most places, it has the capacity of replacing a wide range of

materials, such as clays, sandstone, shale, limestone, and most igneous rocks. Wad is not as stable as the other oxides, however, and if more manganese is brought in, psilomelane, manganite, and pyrolusite tend to form in the order given. As a consequence, in many places where manganese minerals are found, the surface zone contains coherent pyrolusite largely, which is succeeded in depth by loosely coherent psilomelane and manganite; the deepest zone shows only earthy wad (figs. 71–72). In the zone of oxidation, the least oxidized and most hydrous tend to form first; these give way successively to the most oxidized and least hydrous.

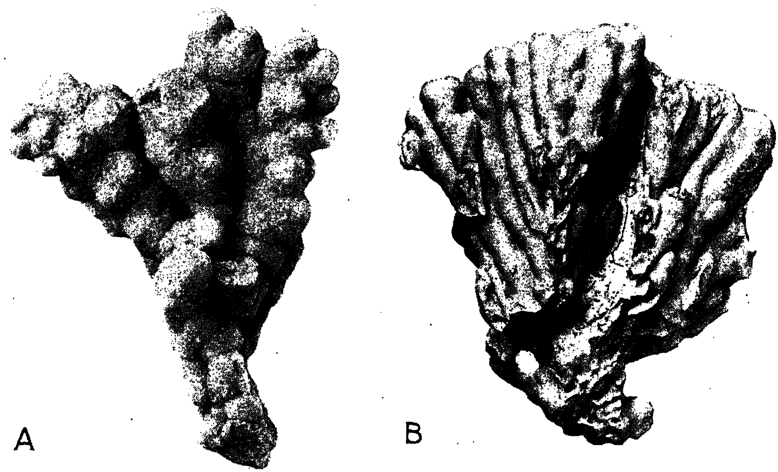


FIG. 72. FORMS OF PSILOMELANE NODULES

1. Irregularly branching, more or less botryoidal cluster. Mount Torry Mine, Virginia, twice natural size. Photograph contributed by G. W. Stose, U. S. Geol. Surv.
2. Radiate cluster of smooth rods, some of which are hollow, Dry Run Mine, Tennessee, natural size. Photograph contributed by G. W. Stose, U. S. Geol. Surv.

As the higher manganese oxides are very stable near the surface, they tend to accumulate on surfaces of planation. Consequently, in many parts of the world, workable bodies of oxides are found on peneplains.[927]

RESEARCH NEEDED

Careful detailed studies of stratigraphic sections containing manganiferous carbonates and oxides are greatly desired and these studies should be

[927] Hewett, D. F., Some manganese deposits in Virginia and Maryland, Bull. 640, U. S. Geol. Surv., 1916, pp. 43–47; Fermor, L. L., op. cit., pp. 370–389; Hummel, K., Über verschiedene Arten von Eisen-manganerzlagerstätten in Deutschland, Zeit. prak. Geol. vol. 35, 1927, pp. 17–21.

supplemented by chemical analyses of carefully selected specimens and by examination of thin sections. Glauconite and phosphatic layers should be sought nearby. Material from mine workings and drill cores remote from the effects of surface oxidation should be sought especially. Thin sections should be examined for traces of organisms which may have caused deposition of the manganese minerals. The work of Dale on the manganese deposits of Newfoundland may be taken as an example of desired investigations. This could have been improved only by closer search for glauconitic material and by a study of the paleogeographic relations of the beds.

There are also needed studies of the changes in manganese content of stream waters from their source to the seas. Further research into the activities of organisms that precipitate manganese is desired.

Sedimentary Deposits of Barium Minerals

Barium as a sediment is not of great quantitative importance. It is locally present in the waters of some wells, springs, and mines as an important part of the solids in solution. The quantity in surface waters is negligible, and it occurs in sea water in very small amounts. Pipes carrying waters from certain British coal mines are known to have become choked with deposits of which in some instances barium was the chief constituent, samples analyzed yielding 81.37 to 93.35 per cent $BaSO_4$.[928] The barium seems to be carried in solution as the chloride and bicarbonate.

Barium is not a common constituent of modern sediments, and such seems to have been the case through all of geologic time. It is stated to be present in small quantities in most marine deposits; some occurs in the manganese nodules of the deep sea;[929] and small, more or less spherical nodules containing 75 per cent $BaSO_4$ have been dredged from a depth of 675 fathoms[930] off the coast of Ceylon near Colombo. The barium in sediments is usually in the form of barite ($BaSO_4$), but it is also occasionally present as witherite ($BaCO_3$). In many cases the formation seems to have been epigenetic, and it was the conclusion of Greenwood[931] that such is its general origin. Barite occurs as incrustations about springs, as oolites and pisolites, as cement for sands, as concretions and crystal growths, and disseminated in sediments. It is not known to be confined to any particular environment.

Oolitic and pisolitic barite has been obtained from oil wells in the Batson and Saratoga oil fields under conditions which indicated that it had formed

[928] Clowes, F., Deposition of barium sulphate as a cementing material of sandstone, Proc. Roy. Soc. London, vol. 46, 1899, pp. 363–368; vol. 64, 1899, pp. 374–377.

[929] Murray, J., and Hjort, J., Depths of the ocean, 1912, p. 190.

[930] Jones, E. J., On some nodular stones obtained by trawling off Colombo in 675 fathoms of water, Jour. Asiatic Soc., Bengal, vol. 56, 1887, pp. 209–212.

[931] Greenwood, H. W., Proc. Liverpool Geol. Soc., vol. 12, 1920, pp. 335–361.

in the oil in the wells, as some of the particles are stated to have been of much larger diameters than the mesh in the screens of the wells. Some contained a core or nucleus which seemed to be pipe scale.[932]

Barite is deposited about some springs as incrustations, as described by Headden about Doughty Springs, Delta County, Colorado.[933] Similar deposits occur about a brine spring in a mine at Lautenthal in the Hartz Mountains,[934] the barium salts being precipitated by the mingling of the sulphate waters of the mine with the brine waters of the spring. Analyses of the dissolved content of the two waters, expressed as grams per liter, are given in table 86. Analyses of the deposits are given in table 87.

TABLE 86

Analyses of Spring and Mine Waters at Lautenthal

	Spring water	Mine water
$BaCl_2$	0.318	
$SrCl_2$	0.899	
$CaCl_2$	10.120	1.515
$MgCl_2$	4.360	0.023
$NaCl$	68.168	4.533
KCl	0.450	
$MgSO_4$		0.652
$ZnSO_4$		0.015

TABLE 87

Analyses of the Spring Deposits at Lautenthal

	White stalactites	Brown stalactites	Mud	Crusts
$BaSO_4$	84.81	83.88	82.30	92.44
$SrSO_4$	12.04	8.64	13.40	4.32

Deposits of barite similar to those of Lauthental occur about certain springs in British coal mines,[935] the deposits also containing strontium. Barite occasionally serves as a cement for sandstones, as in parts of the Chester

[932] Wuestner, H., Pisolitic barite, Jour. Cincinnati Soc. Nat. Hist., vol. 20, 1906, pp. 530–533; Moore, E. S., Oolitic and pisolitic barite from the Saratoga oil field, Texas, Bull. Geol. Soc. Am., vol. 25, 1914, pp. 77–79; Moore, E. S., Additional note on the oolitic and pisolitic barite from the Saratoga oil field, Texas, Science, vol. 46, 1917, p. 342; Suman, J., The Saratoga oil field, Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, p. 275; Barton, D. C., and Mason, S. L., Further note on barite pisolites from the Batson and Saratoga oil fields, Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, pp. 1294–1295.

[933] Headden, W. P., Proc. Colorado Sci. Soc., vol. 81, 1905, p. 1.

[934] Lattermann, G., Jahrb. k. preuss. geol. Landesanstalt, 1888, p. 259.

[935] Dunn, J. T., Chem. News, vol. 35, 1877, p. 140; Richardson, T., Rept. Brit. Assoc., 1863, p. 54.

series of Indiana, the Triassic of England,[936] and this and other sandstones of continental Europe.[937] Barite concretions are in the nature of crystalline growths, usually occurring in sandstone and to a less extent in sandy clays and shales. The shapes are irregular, tabular, and rosette, the last not uncommonly known as petrified roses. Barite in this form has been found in England, Russia, Egypt, Italy, and in the United States in Nebraska, Kansas, Oklahoma, and elsewhere. Those described by Pogue from Egypt are nodules, rounded tablets, and involved intergrowths, with dimensions ranging to 70 mm. in diameter; they contain about 50 per cent barium sulphate cementing quartz sands. The Russian occurrences have been described by Samoilov[938] and assigned to an organic origin.

An analysis of a sand barite rosette from Oklahoma is as follows:[939]

SiO_2	45.13
Al_2O_3	0.88
Fe_2O_3	0.96
H_2O	0.31
P_2O_5	Trace
SO_3	17.87
MnO	0.02
BaO	34.25
	99.42

Disks of barite have been described from the Lias of England by Richardson,[940] where they occur irregularly distributed along bedding planes, the disks having maximum diameter of 15 mm. and maximum thickness of 2 mm. Both upper and lower surfaces were marked by radial furrows. Each disk was found to be a single crystal flattened parallel to 001. Somewhat similar disks, known as barite "dollars," occur in Nebraska.[941]

Barite is not uncommon as a crystal in geodes and the cavities of shells, and in these forms has been found in many parts of the world. It is said to be common in ammonite shells of western Europe.[942]

[936] Clowes, F., op. cit., 1899; Greenwood, H. W., op. cit.; Nichols, H. W., Pub. no. 11, Field Columbian Museum, 1906, p. 31.

[937] Pogue, J. E., On sand-barites from Kharga, Egypt, U. S. Nat. Mus., vol. 38, 1910, pp. 17, et al. Pogue lists the different localities with references to the papers where the occurrences are described.

[938] Samoilov, J. V., Mineralogical Mag., vol. 18, 1917, p. 87.

[939] Shead, A. C., Notes on barite in Oklahoma with chemical analyses of sand barite rosettes, Univ. Oklahoma Bulletin, n. ser., no. 271, 1923, p. 104.

[940] Richardson, W. A., Petrology of the shales-with-"beef," Quart. Jour. Geol. Soc., vol. 79, 1923, pp. 88–89.

[941] Burnett, J. B., Barite "dollars" from Franklin County, Nebraska, Nebraska Geol. Surv., vol. 7, pt. xv, 1916, pp. 105–111.

[942] Collet, L. W., Diffusion du baryum et strontium dans les terrains sédimentaires, etc., Compt. Rend., Acad. Sci., vol. 141, 1905, pp. 832–834; Martens, J. H. C., Barite and associated minerals in concretions in the Genesee shale, Am. Min., vol. 10, 1925, pp. 102–104.

The causes of precipitation of barite are known in a few cases. The deposits in the mine spring at Lautenthal are precipitated by reaction of the sulphate waters of the mine and the barium chloride waters of the spring. In other instances, as in British coal mines, it may have been precipitated from barium bicarbonate waters consequent to loss of carbon dioxide on these waters reaching the surface. This barium would be in the form of witherite. Barite is also precipitated from waters carrying the bicarbonate of barium at places of contact with gypsum, or oxidizing iron sulphide.[943] Its occasional presence in limestone may be due to this latter reaction. Schulze[944] and Chevotiev[945] observed granules of barite in the bodies of certain rhizopod protozoans, and thus it is probable that in some occurrences barite is of organic origin.

Sedimentary Deposits of Strontium Minerals

Strontium as a sedimentary product occurs as celestite ($SrSO_4$) and strontianite ($SrCO_3$). Both are rare, but celestite seems to be more common than strontianite.

Strontium is found in ordinary surface waters as mere traces, but in some springs it is present in comparatively large quantities, the mine spring at Lautenthal in the Hartz Mountains[946] containing 0.899 grams of strontium chloride per liter, nearly three times as great a quantity as the barium chloride present. Water from a gas well in Washington County, Pennsylvania, contained strontium to the extent of 1.31 per cent of the solid matter in solution. It is also found in small quantities in ocean waters.[947]

Strontium is carried in solution as the chloride, sulphate, and bicarbonate, and since the sulphate is more soluble than calcium carbonate, it may be removed in solution from deposits of the latter.

Strontium is not detectable by ordinary methods in most recent marine sediments. Some manganese nodules contain the element in extremely small quantities.[947]

The element is a deposit of certain springs, where it occurs as incrustations, in the form of celestite and less commonly as strontianite. Common associates are barite, as at the Lautenthal springs, sulphur, and gypsum. It is a characteristic deposit of certain of the springs of Sicily, where it is

[943] Dickson, C. W., School of Mines Quart., vol. 23, 1906, p. 366.

[944] Schulze, F. E., Wissenschaftliche Ergebnisse der deutschen Tiefsee-expedition auf d. Dampfer "Valdivia," vol. 11, 1905, L. 1, p. 14.

[945] Referred to by Samoilov, op. cit., The original article is in Russian and was published in Petrograd in 1910.

[946] Lattermann, G., Jahrb. k. preuss. geol. Landesanstalt, 1888, p. 259.

[947] Clarke, F. W., Data of geochemistry, Bull. 770, U. S. Geol. Surv., 1924, pp. 124, 187, 589.

associated with sulphur and gypsum, the original source of the strontium being thought to be subterranean molten rock.

Both celestite and strontianite occur as disseminated crystals in other rocks and in cavities of various kinds. Crystals of celestite are disseminated through dolomite in Monroe County, Michigan, parts of the upper part of the dolomite containing 14 per cent celestite. Cavities in the lower part of the same rock contain celestite and considerable quantities of sulphur.[948] In Schoharie County, New York, celestite occurs in limestone in the form of pockets and thin layers, and in Oneida County of the same state both celestite and strontianite are found in geodes of the Clinton limestone, the latter in the outer part and the former within. The two minerals exist together in the rocks of Jefferson County, New York, and celestite is abundantly disseminated through a dolomitic limestone near Syracuse, New York.[949] A famous locality for celestite is Put-in Bay, Lake Erie, where a cave was found in 1897 whose ceiling, walls, and floor were covered with celestite crystals, and celestite is said to have been present for 22 feet beneath the floor.[949] Celestite is present in the Glen Rose limestone near Austin, Texas, in the form of nodules and pockets, with strontianite, epsomite, calcite, and aragonite as associated minerals. Some of the celestite nodules are stated to have weighed as much as 100 pounds. Celestite occurs at Cedar Cliff, Mineral County, West Virginia, filling cavities a yard in diameter and 3 to 7 inches high,[950] and as a cement for sands it is found in the Oriskany sandstone of western New York.[951] Strontianite deposits near Barstow, California, are in the form of beds and lenses interstratified with limestones and shales of lacustrine origin. The general relations suggest contemporaneous deposition with the associated sediments, but the detailed structures and textures of the strontianite seem best interpreted as due to replacement of limestone beds by cold (?) meteoric waters.[952] An extremely interesting occurrence of celestite lies on the south margin of the Avawatz Mountains in San Bernardino County, California, where the celestite with a maximum thickness of 75 to 80 feet is interstratified with beds of salt, gypsum, and clay of lacustrine deposition. The celestite contains

[948] Kraus, E. H., and Hunt, W. F., The occurrence of sulphur and celestite at Maybee, Michigan, Am. Jour. Sci., 4th ser., vol. 21, 1906, p. 237 et al.

[949] Kraus, E. H., The occurrence of celestite near Syracuse, New York, and its relation to the vermicular limestones of the Salina epoch, Am. Jour. Sci., vol. 18, 1904, pp. 30–39; Occurrence and distribution of celestite-bearing rocks, Ibid., vol. 19, 1905, pp. 286–293.

[950] Williams, G. H., Celestite from Mineral County, West Virginia, Am. Jour. Sci., vol. 39, 1890, pp. 183–188.

[951] Stone, M. H., An occurrence of Oriskany sandstone with celestite cement, Am. Jour. Sci., vol. 16, 1928, pp. 446–450.

[952] Knopf, A., Strontianite deposits near Barstow, California, Bull. 660, U. S. Geol. Surv., 1918, pp. 257–264.

more or less clastic material, gypsum, and iron and manganese oxides. Contemporaneity with the associated sediments is suggested, but replacement of carbonate beds is possible.[953] Celestite and barite occur together in a bituminous limestone of Transylvania.[954] The nummulitic limestone of Egypt contains celestite crystals which in some instances enclose fossils and in others fill the interiors of fossil shells.[955] This deposit has been considered by some as syngenetic with the associated sediments; others have held that the strontium was leached from overlying strata by ground water.[956]

Most of the strontium deposits which have been described seem to be of epigenetic origin, and only in the cases of deposition from spring waters is contemporaneity established. In a few instances doubt exists. The extreme rarity of strontium in solution renders it probable that contemporaneous deposits are rare and local.

Strontium in solution in natural waters is acquired from the rocks through which the waters circulate. Waters circulating through limestones would extract any strontium sulphate, leaving the calcium carbonate because of its greater relative insolubility. Precipitation might be accomplished where these waters reached cavities or the surface, or met other waters of differing content, leading to reaction and precipitation. This would take place where strontium chloride waters mingled with those containing sulphates. The bicarbonate of strontium is probably precipitated by loss of carbon dioxide. It is possible that some strontium is precipitated through the agency of life, as it has been detected in the shells of certain mollusks and corals,[957] and it is known to be present in the ash of some seaweeds.[958] An interesting bit of information in this respect is the brilliant discovery of Butschli that the shell of the radiolarian *Podactinelius* and the shells of the acantharian radiolarians, in general, are almost wholly composed of strontium sulphate.[959] Samoilov suggested an organic origin for the celestite which is stated to have extensive distribution in Turkestan.[960]

[953] Phalen, W. C., Celestite deposits in California and Arizona, Bull. 540, U. S. Geol. Surv., 1904, pp. 526–531.

[954] Koch, A., Neue Fundorte des Cölestin in Siebenbürgen, Tschermak's Min. pet. Mitth., vol. 4, 1877, pp. 317–320; Ein neues Cölestin- und Barytvorkommen in den Siebenbürgen, Ibid., vol. 9, 1888, pp. 416–422.

[955] Bauermann, M., and Foster, C., On the occurrence of celestite in the nummulitic limestone of Egypt, Proc. Geol. Soc. London, vol. 25, 1868, pp. 40–44.

[956] Andrée, K., Über den Cölestin in Mokattamkalk von Egypten, etc., Neues Jahrb. f. Min. etc., Beil.-Bd. 37, 1914, pp. 374–386. This paper reviews many of the then known occurrences of celestite, pp. 343–374.

[957] Vogel, O., Zeits. anorg. Chem,. vol. 5, 1894, p. 55.

[958] Dieulafait, L., Compt. Rend., Acad. Sci., Paris, vol. 84, 1877, p. 1303.

[959] Butschli, O., Chemische Natur der Skelettsubstance des Podactinelius und der Acantharia überhaupt, Naturwiss. Wochenschr., vol. 6, 1907, pp. 429–430. From Deutsch. Südpol. Exped., Bd. 9, Heft 4.

[960] Samoilov, J. V., Mineralogical Mag., vol. 18, 1917, pp. 87–98.

Sedimentary Deposits of Sulphur

Native sulphur of sedimentary origin is not uncommon in recent and ancient sediments, usually occurring as isolated particles, but sometimes present as beds, lenses, and bodies of various form. Many deposits of sulphur seem to be related to igneous processes, and the origin of some of the largest occurrences is unknown. Consideration is given only to those occurrences for which the evidence of sedimentary origin is strong.

The common associates of sulphur of sedimentary origin are gypsum, lime carbonate, and organic matter, the last usually in the form of black shale. It is precipitated from sulphates and hydrogen sulphide in solution, and from colloidal sulphur which is present in water under certain conditions; and it also forms one of the decomposition products of metallic sulphides.

ENVIRONMENTS AND AGENTS OF DEPOSITION OF NATIVE SULPHUR

Native sulphur seems to form and be deposited in four sedimentary environments: (1) the surface and the zone of weathering, through decomposition of metallic sulphides; (2) about springs; (3) in bodies or parts of bodies of water low in oxygen, so that reducing conditions and anaërobic bacteria prevail; and (4) in lakes into whose waters there are being brought volcanic gases containing sulphur.

The decomposition of metallic sulphides may yield sulphur as powdery efflorescences on the surface and as crystals in cracks and cavities. The latter may perhaps be exemplified by the native sulphur in some Michigan geodes. The former is excellently shown in south central Kansas over some portions of the exposed surfaces of the Cheyenne sandstones and the Kiowa shales, the two formations containing much pyrite from whose decomposition the sulphur is derived. The possibilities of sulphur of this environment assuming significant dimensions are rather limited.

Native sulphur, commonly associated with gypsum, calcite, and aragonite, is not uncommon about springs whose waters contain hydrogen sulphide, sulphates, and colloidal sulphur. The sulphates are supposed to be reduced by bacteria to hydrogen sulphide, and this oxidizes to water and sulphur. Sulphur may be carried as a colloid in waters which contain sulphur, sulphuric acid, and sodium sulphate in the relations of S 2.79–2.60, H_2SO_4 6.43–7.00, and $NaSO_4$ 3.75–3.92 per cent. If there are changes in the concentration of the salt, sulphur is precipitated.[961] It seems probable that deposits of this environment may be of the same order of magnitude as the spring deposits of other substances.

In the Trans-Pecos region of Texas are deposits of sulphur in Permian

[961] Hunt, W. F., The sulphur deposits of Sicily, Econ. Geol., vol. 10, 1915, pp. 545–546.

and Upper Carboniferous strata associated with gypsum and waters containing hydrogen sulphide of undetermined source. The sulphur and gypsum deposits are also associated with organic matter and limestones, and there are indications that some of the gypsum has been formed through alteration of limestones. The sulphur occurs as thin, amorphous films on gypsum and disseminated through it, one analysis by Steiger showing 18.36 per cent free sulphur. The fact that the sulphur is associated with gypsum and organic matter suggests a genetic relationship. Perhaps the sulphur was formed by reduction of gypsum,[962] and it is probable that sulphur is being deposited at the present time from the hydrogen sulphide escaping from the waters of springs in the same region.

Bodies of water deficient in oxygen below the surface become rich in hydrogen sulphide, which in some waters is so great as to make them unfit for marine organisms, as is the case in the Black Sea, which is habitable

TABLE 88

DEPTH	H_2S PER 100 LITERS
meters	*cc.*
213	0.33
427	2.22
2026	5.55
2528	6.55

to only 7 per cent of the depth.[963] The quantity increases with depth as shown by table 88.[964]

The hydrogen sulphide occurring under these conditions is thought to be in part a decomposition product of the anaërobic bacterial decay of organic matter and in part a product of bacterial reduction of sulphates in solution. Oxidation of the hydrogen sulphide, for which bacteria are also probably in part responsible, leads to precipitation of sulphur. It is possible that sulphur deposits of this origin may attain significant proportions, but it is not known that such are accumulating to any extent at the present time.

It has been found that free sulphur is a common constituent of most samples of marine muds, the quantities ranging from 22 to 104 parts per

[962] Smith, E. A., Notes on native sulphur in Texas, Science, vol. 3, 1896, pp. 657–659; Skeats, E. M., Bull. 2, Univ. Texas Mineral Surv., 1902, pp. 29–42; Richardson, C. B., Bull. 9, Ibid., 1904, pp. 68–71.

[963] Hunt, W. F., op. cit., p. 569.

[964] Lebedinzeff, A., Travaux de la Société des Naturalistes à Odessa, vol. 16, 1891, Ref. by Hunt, W. F., op. cit., p. 569; also by Phalen, W. C., after Stutzer, O., The origin of sulphur deposits, Econ. Geol., vol. 7, 1912, p. 740.

100,000. Microscopical examination made of samples from Florida Bay, deposited in water less than a meter deep, showed minute grains of a yellow waxy substance having the properties of sulphur.[965] As most marine sediments are deposited under reducing conditions, it seems probable that bacterial activity in some way is connected with the occurrence of free sulphur in such sediments.

Sulphur is at present being deposited in certain lakes of some volcanic regions of Japan. The sulphur gases escape through crevices on the lake bottoms, and on contact with the water sulphur is deposited in the form of variously shaped grains of 0.2 to 3 mm. diameter. The grains are hollow and have kidney, fig, hemispherical, and spindle shapes. Although there are some features connected with the origin of this sulphur which are not sedimentary, its final deposition takes place through sedimentary processes.[966]

Sulphur is associated with some of the salt domes which are found in certain parts of the world. It is possible that this sulphur is the result of sedimentary processes, but the formation occurred at considerable depths and at temperatures probably higher than those normal to the surface.

SULPHUR DEPOSITS IN THE GEOLOGIC COLUMN

Small occurrences of native sulphur are known in the geologic column, particularly in the later systems. Large deposits are not uncommon in Tertiary rocks, but opinion is greatly divided with respect to the origin of many of these. For this reason the present discussion is limited to that occurrence which has perhaps been the most extensively investigated, and with respect to which the conclusion of a sedimentary origin has been reached by several students.

The most extensive deposits of sulphur for which a sedimentary origin seems probable are those of south central Sicily. Formerly these were considered of volcanic origin, but this view appears to have been abandoned with the working out of the geologic relationships.[967] These sulphur beds are interstratified with bituminous clays, gypsum, and limestone of Miocene and perhaps of lower Pliocene age, some of the associated strata being marine. The deposits are disconnected, and each appears to have a basin-like form. They are commonly underlain by tripoli formed of the tests of radiolaria

[965] Trask, P. D., and Wu, C. C., Free sulfur in recent sediments, Abstract, Bull. Geol. Soc. Am., vol. 41, 1930, pp. 89–90; Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 1462–1463.

[966] Oinonye, Y. A., A peculiar process of sulphur deposition, Jour. Geol., vol. 24, 1916, pp. 806–808.

[967] Data relating to the sulphur deposits of Sicily have been largely derived from Hunt, W. F., op. cit., pp. 543–579; Stutzer, O., Transl. by Phalen, W. C., op. cit., pp. 732–743; and Sagui, C. L., The sulphur mines of Sicily, Econ. Geol., vol. 18, 1923, pp. 278–287.

and skeletal matter of sponges, and overlain by massive gypsum. Crystals of celestite, aragonite, gypsum, and other minerals are associated with the sulphur. The sulphur-bearing beds average 3 to 4 meters in thickness and range from 1 to 30 meters. The character of the sequence is shown in the following section:[968]

	Meters
Bituminous shales	40
Sulphur-bearing layer	6
Bituminous shale	½
Sulphur-bearing layer	5
Bituminous shale	½
Sulphur-bearing layer	6
Tripoli and siliceous limestone	12–20

The sulphur-bearing layers consist of sulphur interlaminated with marly clay or limestone and gypsum. Some bituminous matter is also present. The sulphur layers are less than an inch thick, whereas the separating units are about twice as thick. Sulphur layers are known to extend distances exceeding 650 feet.[969] Some are cross-laminated, and in one exposure a sulphur-bearing layer is unconformably overlain by shale, showing contemporaneous erosion.

The geologic relationships suggest that deposition took place in lagoons more or less disconnected with each other and the sea, the latter effecting entrance at times as indicated by the occurrence of marine fossils in some of the beds. The gypsum is thought to have been deposited during times of high salinity brought about by excess of evaporation in the lagoons over inflow either from sea or land, such high salinity eliminating the sulphate-reducing bacteria held responsible for the formation of the sulphur. It is known that the activities of some sulphate-reducing bacteria cease under such conditions, that of *Spirillum desulfuricum* ceasing when the concentration reaches 3 per cent and that of *Microspira æstuarii* almost ceasing when the concentration rises above 6 per cent.[970] The bacteria reduce sulphates to sulphides, with hydrogen sulphide as an ultimate product. This rises toward the surface and may oxidize to water and sulphur, bacteria assisting in, and perhaps being essential for, such oxidation. The equations supposed to express the various reactions are as follows:

(1) $CaSO_4 + 2\ C$ (living micro-organisms) $= CaS + 2CO_2$

(2) $2CaS + 2H_2O = Ca(OH)_2 + Ca(SH)_2$

(3) $Ca(OH)_2 + Ca(SH)_2 + 2CO_2 = 2CaCO_3 + 2H_2S$

(4) $H_2S + O = H_2O + S.$

[968] Hunt, W. F., op. cit., p. 554.
[969] Stutzer, O., in Phalen, W. C., op. cit., pp. 735–736.
[970] Hunt, W. F., op. cit., p. 3.

The calcium hydrosulphide, coming in contact with sulphur settling from above, might react therewith to form a calcium polysulphide and liberate hydrogen sulphide as expressed in equation (5).[971] As this reaction is reversible, any hydrogen sulphide coming in contact with the polysulphide would precipitate free sulphur, so that at times a larger precipitation than ordinary might take place.

$$Ca(SH)_2 + 4S = CaS_5 + H_2S \tag{5}$$

Other living bacteria which are concerned in processes like the above are *Proteus vulgaris*, *Bacterium mycoides*, *B. hydrosulfureum*, and *Vibrio hydrosulfureus*.[972]

The history of the Sicilian sulphur deposits is thought to have been somewhat as follows: During times of great bacterial activity there was large precipitation of pure sulphur. This precipitation was interrupted from time to time by the deposition of mud and calcium carbonate. Times of great evaporation or decreases in the quantities of water supplied to the basins produced concentration too high for bacterial activity, and at these times the products of concentration were deposited. Entrance of the sea brought in marine sediments.

Sagui[973] considers that the hydrogen sulphide was derived from an intrusion of basaltic lava from which it was washed by underground water and brought to the basins of deposition in springs. The gypsum is thought to have developed as a consequence of reactions between calcium carbonate, water, and sulphur.

Sedimentary Feldspar

Feldspar occurs in sediments as fragments derived from pre-existing rocks and apparently as an original development. The former occurrences are well known and have been considered to some extent in connection with arkose, and it of course follows that detrital feldspar may be found in any variety of sedimentary rock. Feldspar as an authigenic mineral, however, is not so well known and has not received a great deal of consideration in America, the first American paper thereon having been published in 1917.[974] The literature was partly summarized in that paper, and a more complete summary with an excellent bibliography was published by Spencer in 1925.[975]

[971] Divers, E., and Shimidzu, T., Jour. Am. Chem. Soc., vol. 45, 1884, p. 283.

[972] Harder, E. C., Iron-depositing bacteria and their geologic relations, Prof. Paper 113, U. S. Geol. Surv., 1919, pp. 41–42.

[973] Sagui, C. L., op. cit., pp. 281–282.

[974] Daly, R. A., Low temperature formation of alkaline feldspars in limestones, Proc. Nat. Acad. Sci., vol. 3, 1917, pp. 659–665.

[975] Spencer, E., Albite and other authigenic minerals in limestone from Bengal, Mineralogical Mag., vol. 20, 1925, pp. 365–381.

Feldspar which bears all the evidence of being authigenic and a sedimentary product seems to be largely confined to calcareous sediments, but an occurrence in Triassic sandstones in northeast Ireland has been described by Reynolds,[976] and Van Hise cites occurrences in the Keweenawan sandstones of the Lake Superior region. The feldspar in most instances is albite, but in one instance the minerals were determined as microcline,[977] and in two instances as orthoclase.[978] The crystals are invariably small and mostly microscopic, but those studied by Spencer from the Cuddapah limestones of Bengal ranged to 10 mm. long. Others studied by Spezia[979] from a foraminiferal limestone of Argentea, Italy, ranged to 3 mm. long, those described by Foullon[980] from Eocene limestone of the Island of Rhodes ranged to the same length, and Issel[981] has described albite tablets from Eocene rocks of Pavia up to 11 mm. long. He considered them of hydrothermal origin, but it may be that such is not the case.

Feldspar of sedimentary origin has been reported from the Pre-Cambrian along the International Boundary between Montana and Alberta[982] and of the Lake Superior region, the Cuddapah (Pre-Cambrian?) system of India,[983] the Ordovician of New York,[984] the Carboniferous limestone near Moscow,[985] and Triassic, Jurassic, and Cretaceous rocks of various parts of Europe. It is not thought essential to describe all occurrences, but detail deemed sufficient for appreciations of characteristics and differences will be given.

The feldspar from the Pre-Cambrian of the International Boundary region

[976] Reynolds, D. L., Some new occurrences of authigenic feldspar, Geol. Mag., vol. 66, 1929, pp. 390–399.

[977] Grandjean, F., Propriétés optiques et genèse du feldspath néogène des sediments du bassin de Paris, Compt. Rend. Acad. Sci. Paris, vol. 148, 1909, pp. 723–725; Le feldspath néogène des terrains sédimentaires non métamorphiques, Bull. Soc. Franç. Min., vol. 32, 1909, pp. 103–133; Deuxième note sur le feldspath néogène des terrains sédimentaires non métamorphiques, Bull. Soc. Franç. Min., vol. 33, 1910, pp. 92–97.

[978] Daly, R. A., Mem. 38, Geol. Surv. Canada, 1912, pp. 50; op. cit., pp. 662–663; Cayeux, L., Existence de nombreux cristaux de feldspath orthose dans la craie du bassin de Paris. Preuves de leur genèse in situ, Compt. Rend. Acad. Sci. Paris, vol. 120, 1895, pp. 1068–1071.

[979] Spezia, G., Sul calcare albitifero dell' Argentea (Cuneo), Atti R. Accad. Sci. Torino, vol. 15, 1880, pp. 785–788.

[980] Foullon, H. B., Über Gesteine und Minerale von der Insel Rhodus, Sitzb. Akad. Wiss., Wien, Math.-Naturw. Cl., vol. 100, Abt. 1, 1891, pp. 144–176.

[981] Issel, A., Radiolaires fossiles contenues dans les cristaux d'albite, Compt. Rend. Acad. Sci. Paris, vol. 110, 1900, pp. 420–424; Il calcifira fossilifero di Rovegno in val de Trebbia, Ann. Mus. Civ. Storia Nat. Genova, vol. 9, 1890, pp. 91–119.

[982] Daly, R. A., op. cit., 1912.

[983] Spencer, E., op. cit.

[984] Singewald, J. T., jr. and Milton, C., Authigenic feldspar in limestone at Glen Falls, New York, Abstract, Bull. Geol. Soc. Am., vol. 40, 1929, p. 94.

[985] Grandjean, F., op. cit., 1909, 1910.

was described by Daly as occurring in the unmetamorphosed Waterton dolomite, of which some laminæ are filled with well-formed crystals of glass-clear orthoclase with diameters of 0.01 to 0.05 mm., and others contain clumps and isolated crystals of orthoclase. Some crystals of albite also seem to be present. A remarkable fact of this occurrence is that the feldspars in places compose 40 per cent of the rock. Van Hise[986] has described Keweenawan sandstones of the Lake Superior region whose cementation is said to be due largely to enlargement of fragments of both orthoclase and plagioclase, the later-deposited feldspar being in optical continuity with that of the old particles. The feldspars of the Cuddapah system described by Spencer[987] are of albite and occur in zones in a massive limestone (not dolomite), the boundaries of the zones not being very definite, but the zones extending vertically through 150 feet and traced along the strike for about three-fourths of a mile. The crystals usually are thinly scattered through the zones, but occasionally are crowded together. Solution of the limestone shows associated minerals to be quartz, mica, pyrite, tourmaline, rutile, sphene, zircon, and garnet, and it is suggested that some of the quartz, mica, tourmaline,[988] sphene, and rutile may be authigenic; the pyrite is quite certainly such. The albite crystals show Carlsbad twinning and have certain peculiarities not explained by that manner of twinning. Crystals range in dimensions to a little over a centimeter in their greatest length, but the cleanest and best developed usually are 1 to 2 mm. long, with the thickness ranging from about one-tenth to one-fifth of the length. Two analyses of crystals gave:

	(1) *Per cent*	(2) *Per cent*
SiO_2	66.95	67.10
Al_2O_3	19.72	19.95
Fe_2O_3	0.50	0.55
CaO	0.66	0.50
MgO	0.88	0.70
K_2O	0.52	0.60
Na_2O	9.95	10.30
Ignition	0.63	0.85
	99.81	100.55

Spencer considers that the perfection of the feldspar crystals precludes their being detrital, and she rejects the possibility of an anamorphic origin

[986] Van Hise, C. R., Enlargement of feldspar fragments in certain Keweenawan sandstones, Bull. 8, U. S. Geol. Surv., 1884, pp. 44–47.

[987] Spencer, E., op. cit., 1925.

[988] Wichmann, H., had previously reported authigenic tourmaline in sandstones, Neues Jahrb. f. Min., vol. 2, 1880, p. 294.

for them. The feldspar from the Ordovician limestones of New York was found in the insoluble residue of the limestones of which it was an abundant constituent. The crystals are euhedral. The sedimentary feldspars of the Triassic, Jurassic, and Cretaceous of the European Alpine region have been described by Heim,[989] Trumpy,[990] Kaufmann,[991] Lory,[992] Rose,[993] Drian,[994] de Stefani,[995] Spezia,[996] Lacroix,[997] Issel,[998] Grandjean, de Lapparent,[999] and others. Essentially all of these occurrences are in unanamorphosed, fine-grained, fossiliferous limestones. The feldspars are mostly albite, and in the case described by Heim small crystals of ankerite were also found. Pyrite and doubly terminating quartz crystals are associated. Kaufmann observed that the feldspars occur rather abundantly in nodular and geodic concretions. The crystals described by the above students are small but euhedral, with maximum lengths of about 0.2 mm., but commonly ranging between 0.05 and 0.08 mm. The feldspar crystals in the Triassic sandstones of northeast Ireland[1000] are stated not to resemble exactly any species recorded from igneous rock. Their optical properties are stated to be those of an orthoclase, but an excess of potash over soda allies them to microcline. Their specific gravity, 2.54, is lower than that recorded for any feldspar. Reynolds also described authigenic feldspar from the Keuper marl, the Dolomitic Conglomerate (base of Keuper), and the Magnesian Limestone (Permian), and Cayeux[1001] has described it from the Chalk of the Paris

[989] Heim, A., Beitrag geol. Karte Schweiz, vol. 20, 1916, pp. 514–567.

[990] Trumpy, D., Beitrag geol. Karte Schweiz, vol. 46, 1916, pp. 83–108.

[991] Kaufmann, F. J., Beitrag geol. Karte Schweiz, vol. 24, 1886, pp. 581–584.

[992] Lory, C., Bull. Soc. Géol. France, vol. 18, 1861, pp. 806–826; Ibid., vol. 23, 1866, pp. 480–497; Rev. Soc. Savantes, Sci. Math. Phys. Nat., Genève, vol. 2, 1868, pp. 235–239; Arch. Sci. Phys. Nat., Genève, vol. 16, 1886, pp. 237–239; Compt. Rend. Acad. Sci. Paris, vol. 105, 1887, pp. 99–101; Compt. Rend. Congr. Géol. Intern., 1891, pp. 86–103; Bull. Soc. Statist. Isère, vol. 14, 1890, p. 228.

[993] Rose, G., Über die Krystallform des Albits von dem Roc-tourne und des Albits in Allgemeinen, Pogg. Ann. Phys. Chem., vol. 125, 1865, pp. 457–468.

[994] Drian, A., Notice sur les cristaux d'albite renfermés dans les calcaires magnésiens des environs de Modane, Bull. Soc. Géol. France, vol. 18, 1861, pp. 804–805.

[995] de Stefani, C., Atti. Soc. Toscana Sci. Nat. Pisa, Proc. Verb., vol. 2, 1879, pp. 202–206.

[996] Spezia, G., op. cit.

[997] Lacroix, A., Bull. Soc. Franç. Min., vol. 11, 1888, pp. 70–71; Minéralogie de la France, vol. 2, 1896, pp. 158–168.

[998] Issel, A., op. cit.

[999] de Lapparent, J., Sur les cristaux de feldspaths développés dans les calcaires du Crétacé supérieur pyrénéen, Compt. Rend. Acad. Sci. Paris, vol. 167, 1918, pp. 784–786; Cristaux de feldspath et de quartz dans les calcaires du Trias moyen d'Alsace et de Lorraine, Ibid., vol. 71, 1920, pp. 862–865.

[1000] Reynolds, D. L., op. cit.

[1001] Cayeux, L., op. cit.

Basin, the feldspar being considered orthoclase. Grandjean[1002] also studied the authigenic feldspars of the Chalk and concluded they were microcline.

Tertiary authigenic feldspars have been described by Kaufmann[1003] and Termier[1004] from the Tertiary of the Alpine region and from the Eocene of the Island of Rhodes by Foullon.[1005] All of these occurrences are in limestones, and the crystals from the Paris Basin are small, averaging 0.04 to 0.05 mm. long. The crystals seem to be well formed and always occur singly. In the Island of Rhodes occurrence the enclosing limestone is fine-grained to dense, and the well formed crystals have maximum lengths of 2.5 to 3 mm. These crystals, first described in 1881, represent the earliest finds of macroscopic authigenic sedimentary feldspars.

There is general agreement among most of the students concerned that the feldspars described developed in the sediments, the evidence therefor being the euhedral shapes, the absence of any evidence of transportation, the impossibility of reference to anamorphism, and the relations to fossils. Thus, Lory found microscopic orthoclase within an ammonite shell; Drian, Spezia, and Spencer described carbonaceous matter scattered through albite crystals; and Issel found radiolaria enclosed within them (this last occurrence may be hydrothermal).

The conditions and processes of origin of the sedimentary feldspars are not known, but several observations which may bear on the environment of origin have been made. Cayeux noted that the feldspars of the Chalk of the Paris Basin do not occur in the same beds with glauconite; Spencer pointed out that the authigenic feldspars of the Cuddapah system are confined to the calcite limestones and are not found in the associated dolomite limestones; Lory directed attention to the common occurrence of doubly terminated quartz, pyrite, and bituminous matter in association with orthoclase, and idiomorphic quartz and mica with albite; Grandjean stated that limestones of lacustrine origin do not seem to contain authigenic feldspar; and de Lapparent found that the authigenic feldspars of the Flysch formation of the Alps were limited to the lower zone in limestones consisting of small granules, the granules being ascribed in part to algæ of the *Girvanella* type, suggesting that algæ may in some way be connected with feldspar formation.[1006] Other limestones of the Flysch in which algæ are not obvious do not seem to contain feldspar. To what extent the relationships are

[1002] Grandjean, F., op. cit.

[1003] Kaufmann, F.J., op. cit., p. 583.

[1004] Termier, P. cited by Daly, Proc. Nat. Acad. Sci., vol. 3, 1917, p. 665.

[1005] Foullon, H. B., op. cit.

[1006] de Lapparent, J., De l'elaboration de silice et de calcaires siliceux par les algues du groupe de Girvanella, Compt. Rend. Acad. Sci. Paris, vol. 167, 1918, pp. 999–1001.

causal is very uncertain. The connection with the absence of glauconite may have some significance, but what it is cannot be stated. The occurrence in the limestones but not the dolomites of the Cuddapah system can hardly have any significance, as feldspars are found in dolomites elsewhere. The absence of authigenic feldspars in lacustrine sediments suggests that the salts in solution in sea water may be essential for the formation. If that is the case, the presence or absence of this mineral would be a valuable criterion for differentiation of deposits of fresh and salt water. Whether any weight can be placed on de Lapparent's suggestion is doubtful. That the feldspar crystals in calcareous sediments grew in calcareous muds seems certain. Foullon thought that the albite studied by him had grown during slow deposition of the enclosing calcareous sediments, and Grandjean thought the crystals ceased to form after burial. On the other hand, Reynolds suggests that they may be formed by ground water long after consolidation of the enclosing rock. In most occurrences it is impossible that the rocks were ever subjected to a high temperature. Doelter has assumed that the temperature of formation may have been as great as 100°C.[1007] (212°F.); Daly suggests that it may have been as low as 70°C.[1008] (158°F.). Each of these figures seems too high, and for some of the occurrences much lower temperatures must be assumed. The lowest temperature at which feldspar has been artificially formed is 300°C.[1009]

The facts that authigenic feldspars are usually associated with marine limestones and that these limestones show evidence of originally having contained much organic matter suggest that lime, salt water, and organic matter are concerned in the formation.

Mineral Products of Extra-terrestrial Origin[1010]

In the deposits of the deeper waters of the sea, and very rarely in shallow-water sediments, there occur particles which have been referred to extra-terrestrial origin. A quart of red clay will yield from 20 to 30 small black magnetic spherules which may or may not have metallic nuclei, and 5 or 6 brown spherules with crystalline structure. An equal quantity of globigerina ooze very rarely contains any of these substances, the more common occurrence in red clays probably arising from slowness of accumulation of these sediments.

The black magnetic spherules rarely exceed 0.2 mm. in diameter and have

[1007] Doelter, C., Handbuch der Mineralchemie, Dresden, Bd. 2, 2. Hälfte, 1915, p. 556.

[1008] Daly, R. A., op. cit., 1917, p. 664.

[1009] Chrustschoff, K., Compt. Rend. Acad. Sci., Paris, vol. 104, 1887, p. 602.

[1010] Murray, J. and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, pp. 327–336.

exteriors composed of magnetite, and nuclei mostly of native iron or an iron alloy. Some are without nuclei. The surfaces are very smooth. The brown spherules, which resemble the chondrite variety of meteorite, contain silicon, have a color range from yellowish to brown, and possess a pronounced metallic luster said to be due to a finely laminated structure. The surfaces are striated and not smooth as in the black spherules. These brown spherules are also somewhat larger than the black ones, an average diameter being about 0.5 mm.

Perhaps the particles of moissonite recently identified in the rocks of the southern Mid-continent regions have their origins connected with the falls of meteorites.[1011]

Zeolites of Sedimentary Origin

Only three zeolites: phillipsite, analcite, and apophyllite, occur in significant quantities as sediments. The first has rather wide distribution in certain marine deposits, and the other two are present in considerable abundance in parts of the Green River shales of Utah, Wyoming, and Colorado.

Phillipsite is a hydrous silicate of potassium and calcium, the formula in some cases (Dana) being $(K_2 \cdot Ca)Al_2Si_4O_{12} \cdot 4\frac{1}{2}H_2O$. It is found as free and isolated crystals in purely pelagic clays and oozes wherein it originates as a product of diagenesis. According to Murray and Renard,[1012] the decomposition of volcanic materials is responsible for its production.

Phillipsite has been found over extensive areas in sediments of the deep waters of the central parts of the Pacific and Indian oceans. The crystals are microscopic, as shown by the fact that certain arenaceous foraminifera use them in their tests. Some red clays are said to consist of 20 to 30 per cent crystals of phillipsite. A chemical analysis of phillipsite is as follows:

	Per cent
SiO_2	47.60
Al_2O_3	17.09
Fe_2O_3	5.92
MnO	0.43
CaO	3.20
MgO	1.24
K_2O	4.81
Na_2O	4.08
H_2O	9.15
Loss, organic matter	7.59
	101.11

[1011] Ohrenschall, R. D. and Milton, C., The occurrence of moissonite in sediments, Jour. Sed. Pet., vol. 1, 1931, pp. 96–99.

[1012] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, pp. 400–411.

Analcite has been described by Bradley[1013] from the Green River shales, wherein it occurs as thin, more or less persistent beds resembling sandstones, the individual particles consisting almost wholly of euhedral crystals with dimensions ranging to nearly 2 mm., all the crystals being clouded with dust-like inclusions. The matrix and analcite particle ratios vary from bed to bed, and in those places where the matrix is large the rock has a tuffaceous appearance and consists of chalcedony in which are embedded particles of minerals, strongly suggesting that the entire deposit originally was a volcanic ash. A few crystals of apophyllite, another zeolite, were seen. Analcite and apophyllite also occur as isolated crystals in many of the oil shale beds of the Green River formation, some beds consisting of 16 per cent by weight of analcite and others in excess of 1 per cent of apophyllite. Various volcanic minerals and a little volcanic glass are associated. Bradley explains the Green River zeolites as having formed in place on the bottom of the waters of deposition as a consequence of reactions between various salts dissolved in the waters and the dissolution products of falling volcanic ash. Strangely, no bentonite seems to be associated.

Zeolites have been described by Lacroix[1014] as resulting from the decomposition of granite and other rocks, chabasite, stilbite, and laumontite thus having formed under conditions of low temperature; and it has also been shown that zeolites form in soils.[1015]

Meerschaum or Sepiolite

As noted in the second title relating to analcite, several thin beds of meerschaum, or sepiolite, are also present in the Green River shales, interbedded with chocolate-brown oil shale containing an abundance of glauberite molds filled with calcite. These were seen by Bradley in Duchesne County, Colorado, no bed exceeding 1 cm. in thickness. Bradley related this sepiolite to deposition of magnesia and silica (the latter perhaps in form of a hydrated gel) from water. The composition as recalculated from analysis is as follows:

SiO_2	58.40
Al_2O_3	1.89
Fe_2O_3	0.42
MgO	26.58

[1013] Bradley, W. H., Zeolite beds in the Green River formation, Science, vol. 67, 1928, pp. 73–74; The occurrence and origin of analcite and meerschaum beds in the Green River formation of Utah, Colorado, and Wyoming, Prof. Paper 158, U. S. Geol. Surv., 1929, pp. 1–7.

[1014] Lacroix, A., Compt. Rend. Acad. Sci., Paris, vol. 123, 1896, pp. 761–764.

[1015] Burgess, P. A., and McGeorge, W. T., Zeolite formation in soils, Science, vol. 64, 1926, pp. 652–653.

CaO	0.69
TiO_2	0.10
H_2O	11.86

Except for an occurrence given by Dana in Utah, sepiolite has not been seen elsewhere in North America. It has been described from the Tertiary sediments of the Paris Basin and near Madrid, Spain, by Brongniart[1016] and from the Tertiary of southern France by De Serres.[1017] Dana[1018] cites further occurrences in Asia Minor, Moravia, and Morocco.

Miscellaneous Sedimentary Products

There is a considerable variety of other substances which have a more or less rare development as sedimentary products. Only a few of these are considered, most being disregarded because of rarity or ignorance respecting occurrences, or of processes and environments to which origin is due.

Iron sulphates are deposited about some springs in small quantities, and mine waters carry zinc, lead, copper and other compounds and make deposits containing these substances in various places. Likewise, lead, zinc, copper and other deposits undergo secondary enrichment from the zone of weathering, the minerals deposited in the secondarily enriched zone usually being oxides or carbonates. Zinc sulphide deposits from mine waters are known in the Joplin district of Missouri[1019] and most geologists seem to be of the opinion that the lead and zinc deposits of the Tri-state district of Kansas, Missouri, and Oklahoma and southwestern Wisconsin were deposited by cold waters after having been dissolved from the surrounding limestones in which they had originally been deposited in widely disseminated condition by the ordinary processes of sedimentation.

Copper seems to have many of its compounds deposited by sedimentary processes. Veins of copper sulphides are oxidized and carbonated in the upper portions by meteoric waters, the compounds thus produced are taken into solution, and are carried downward to be deposited as cuprite (Cu_2O), tenorite (CuO), malachite ($Cu_2(OH)_2,CO_3$), and azurite ($Cu_3(OH)_2(CO_3)$). Even chalcocite (CuS) has been formed under ordinary sedimentary conditions, Winchell[1020] having treated cupriferous pyrite with dilute solutions

[1016] Brongniart, A., Le magnésite du bassin de Paris, Ann. des Mines, vol. 7, 1822, pp. 303–304.

[1017] De Serres, M., Mémoire sur les terraines d'eau douce, Jour. Physique, vol. 87, 1818, pp. 134–135.

[1018] Dana, E. S., A text-book of mineralogy, 1906, p. 480.

[1019] Robertson, J. D., On a new variety of zinc sulphide from Cherokee County, Kansas, Am. Jour. Sci., vol. 40, 1890, pp. 160–161; Iles, M. W. and Hawkins, J. D., Eng. and Min. Jour., vol. 49, 1890, p. 499.

[1020] Winchell, H. V., Synthesis of chalcocite and its genesis at Butte, Montana, Bull. Geol. Soc. Am., vol. 14, 1903, pp. 269–276.

of copper sulphate and sulphur dioxide and obtained films of cuprous sulphide. Bronze articles about some of the Swiss lake-dwellings have been found coated with chalcopyrite.[1021] The Permian Kupferschiefer of Germany contain copper minerals in wide distribution and the minerals are generally referred to deposition by sedimentary processes. The enclosing materials are dark shales which seem to have been deposited in shallow waters of such character as to be highly reducing. The copper minerals are chiefly bornite, chalcocite, and chalcopyrite. Native silver is also present in the ratio of about 1 part silver to 200 parts copper, and zinc and lead are common. The Kupferschiefer have been extensively worked for the copper which they contain. Most students have considered the copper minerals to be syngenetic with the enclosing shales, and the precipitation of the copper minerals by some has been referred to decaying organic matter, Thiel suggesting that bacteria may have been responsible.[1022]

Native copper in unanamorphosed sediments is found occasionally. Haworth and Bennett[1023] have described films of native copper near Enid, Oklahoma, existing under conditions where it must have been deposited by cold waters. Native copper has also been found as impregnations of fossil wood in the Permian of Texas.[1024] Lovering[1025] has described the occurrence of metallic copper in thin beds of black muck, full of organic remains and interstratified with sands and gravel, in a bog near Cooke, Montana. No copper occurs in the sands and gravels. The copper is in the form of extremely spongy masses which range from minute specks to lumps more than an inch in diameter. The copper is assumed to have been derived from sulphide copper lodes in the surrounding higher lands and to have been carried to the bog in solution as cupric salts, where it is thought to have been precipitated by micro-organisms living in the muck. Experiments showed that the micro-organisms were able to live in a 1/2500 solution of copper and to precipitate metallic copper from a copper sulphate solution whose concentration in copper ranged from 1/10,000 to 1/50,000. Three possible causes of precipitation were considered: adsorption by colloids, reduction of copper sulphate by waste products of the micro-organisms, and

[1021] Chuard, E., Compt. Rend., Acad. Sci. Paris, vol. 80, 1875, p. 1297.

[1022] Thiel, G. A., The influence of bacterial action in the deposition of the Kupferschiefer of Germany, Econ. Geol., vol. 21, 1926, pp. 299–300. For a review of the literature relating to the copper minerals in the Kupferschiefer, the reader should consult Trask, P. D., Origin of the ore of the Mansfeld Kupferschiefer, Germany. A review of current literature, Econ. Geol., vol. 20, 1925, pp. 746–761. Trask's paper gives a bibliography.

[1023] Haworth, E., and Bennett, J., Native copper near Enid, Oklahoma, Bull. Geol. Soc. Am., vol. 12, 1901, pp. 2–4.

[1024] Schmitz, E. J., Trans. Am. Inst. Min. Eng., vol. 26, 1896, p. 101.

[1025] Lovering, T. S., Organic precipitation of metallic copper, Bull. 795, U. S. Geol. Sur., 1928, pp. 45–52.

consumption of the sulphate by such organisms, with precipitation of native copper. Experiments seemed to demonstrate that the second method would account for the copper and that the first and third hypotheses were inadequate. Percy[1026] mentions a deposit of peat in Wales which has actually been worked as a copper ore, the ash of the peat containing 3 per cent of copper.

The circulation fluids of many mollusks and arthropods have a greenish color due to the presence of a copper protein known as hæmacyanin, and the decay of such organisms must lead to the deposition of some copper in sediments. Studies made by Galtsoff and Whipple[1027] show that the pigment which colors some oysters green is due to copper, not in the form of hæmacyanin or a copper proteinate of any kind, but in a highly disassociated unknown state. It was found that the "Copper content of normal oysters varies between 8.21 to 13.77 milligrams per 100 grams dry weight, or from 0.16 to 0.248 milligrams per oyster. Copper content of green oysters analyzed during the investigation varied between 121.71 and 271.91 milligrams per 100 grams dry weight, or from 1.24 to 5.12 milligrams per oyster." With such extensive utilization of copper by organisms—and there probably has been considerable range in its use throughout geologic time—it should not be difficult to account for the quantities found in some formations.

It has lately been stated that under some conditions waters of surface temperatures transport and deposit gold, the transportation and deposition not being in the form of clastic gold.[1028] It was found that the gold in sands and gravels in Brazil increased between the first and second workings and that the gold responsible for the increase was different from that present in the first working. The conditions limited the transportation to cold water. It was concluded that gold is attacked and removed by humic acids under conditions excluding oxygen, provided sufficient time is given. The conclusions are supported by experimental data and the field evidence indicates that concentration of gold is related to the plant growth above the containing sands and gravels. There is also presented in support of the conclusion the fact that the diamond-bearing conglomerates of Minas Geraes are partly cemented by gold deposited from solution. The experiments also showed chemical removal of palladium.

Leucoxene, a decomposition product of ilmenite, is a not uncommon substance in some sediments, but it does not seem to have been frequently

[1026] Percy, J., Metallurgy, vol. 1, 1875, p. 211.

[1027] Galtsoff, P. S. and Whipple, D. V., Oxygen consumption of normal and green oysters, Bull. Bureau Fisheries, vol. 46, 1930, pp. 489–508.

[1028] Friese, F. W., The transportation of gold by underground solutions, Econ. Geol., vol. 26, 1931, pp. 421–431.

identified in American sedimentary formations, only a single instance having come to the author's attention.[1029] However, studies made of Chester sandstones of southwestern Indiana show that the most common heavy minerals are leucoxene, rutile, and brookite. The leucoxene in part seems to have developed from the ilmenite, and crystals of rutile and brookite are present in the leucoxene and the associated sands, seeming to indicate that these minerals developed from the leucoxene after its deposition in the sandstones, the change having been effected under conditions of little pressure and low temperature.[1030]

[1029] Brown, L. S., The occurrence of leucoxene in some of the Permian Mid-Continent sediments, Am. Mineralogist, vol. 13, 1928, pp. 233–235.

[1030] McCartney, G., A petrographic study of the Chester sandstones of Indiana, Jour. Sed. Pet., vol. 1, 1931, pp. 82–90.

CHAPTER VI

STRUCTURES, TEXTURES AND COLORS OF SEDIMENTS

Structures of Sediments and Their Origins

Structures of sediments include stratification, cross-lamination, unconformities, ripple mark, wave mark, rain prints and similar impressions, mud cracks, ice crystal impressions, clay galls, concretions, contemporaneous deformation, tracks and trails, and various features difficult of classification.

STRATIFICATION

Stratification, or arrangement in layers, is without doubt the most distinctive structural feature of sedimentary rocks. It is also a feature concerning which not a great deal with respect to origin is known. A *stratum* is defined as a layer which is separable along bedding planes from layers above and below, the separation arising from a break in deposition or a change in the character of the materials deposited.[1] The stratification is due to some change in the color, size, composition, etc., of the sediments deposited at a given place, or to some interruption in deposition, permitting a change to take place in the materials already deposited. According to some usage, the term "stratum" includes all continuous layers composed of the same kind of material; in this sense it carries the significance of a formation. A stratum may be stratified. If thin, these units are known as *laminæ*, or laminations, terms which have also been applied to thin strata. The upper limit of a lamination is indefinite, but may be placed at about one-half inch. In addition to laminæ, a stratum not uncommonly contains larger non-separable units which are indicated by changes of texture, organic content, concretions, etc. These may be termed *stratum layers.* Laminæ range from parallelism to high angles with bedding planes. The latter are considered under the topic of cross-lamination.

Stratification may be direct or indirect. Direct stratification takes place when physical and other changes bring different types of sediment to the sites of deposition. Indirect stratification results when sediments, after their initial deposition, are thrown into suspension by wave action and

[1] Walther, J., Einleitung in die Geologie, etc., 1894, pp. 620–621; see also Andrée, K. Wesen, Ursachen und Arten der Schichtung, Geol. Rundschau, Bd. 6, 1915, pp. 351–397.

redeposited in layers based on differences in dimensions and specific gravities of particles.[2]

Regularity of stratification planes is more common in chemical and some organic sediments than in those of purely mechanical origin, but the latter may have considerable regularity of stratification planes.[3]

Many deposits do not show detailed stratification and it is probable that this in many cases is due to working over of the bottom materials by organisms which in their search for food bring about a more or less complete mixing of the materials and destroy any detailed stratification which may have been present.

Initial Inclination

Stratification approximates parallelism to the surface on which deposition takes place. This may be horizontal or inclined; in most instances it is probable that there is some inclination, as the present surfaces of deposition are "undulating. The deposit formed in any particular century has marked basins, monoclines, and anticlines that are not due to deformation after deposition."[4] The tendency is for the lower portions of a surface to receive thicker deposits, with the result that each successive stratum is deposited on a less inclined slope. This, however, is not always the case, and variations in deposition may make a new surface of greater irregularity than the old, and contemporaneous erosion of deposits may create extremely steep slopes. The steepest slope on and at which it seems possible for sediments to be deposited was given by Thoulet as 41°.[5] Walther states that sediments may be deposited in orderly sequence upon surfaces inclined as much as 30°.[6] Any agitation of the medium in which deposition takes place flattens the angle of deposition. Studies made on this problem by Miss M. B. Draper[7] gave results as follows:

> The tendency is for larger grains to stand at slightly steeper angles under water than smaller grains.
>
> Angular grains tend to stand at slightly steeper angles under water than rounded grains of the same size.

[2] Walther, J., Einleitung in die Geologie, etc., 1894, p. 631; Perry, N. W., The Cincinnati rocks, Am. Geol., vol. 4, 1889, pp. 326–336.

[3] A classification of stratification, based on the character and position of the units, has been proposed by Andrée. Andrée, K., Das Meer und seine geologische Tätigkeit, in Salomon (ed.), Grundzüge der Geologie, Bd. 1, 1924, p. 427.

[4] Shaw, E. W., Bull. Geol. Soc. Am., vol. 31, 1920, pp. 124–125.

[5] Thoulet, J., Ann. Chim. et Phys., vol. 12, 1887, pp. 33–64.

[6] Walther, J., op. cit., pp. 620–621; Andrée, K., op. cit., 1915, pp. 359–362.

[7] Draper, M. B., Maximum initial subaqueous dips of sediments, etc. Unpublished thesis, Univ. of Wisconsin, 1930.

The highest angle attained was 43 degrees with sands, mesh 8–14, mixed angular and subangular. The lowest maximum inclination was 33 degrees, with rounded grains, mesh 100–200. For medium sized sand grains, mesh 28–48, 35 degrees was found to be the maximum for rounded grains and 38 degrees for angular grains.

There is always a thinning of clay on the upper part of a slope regardless of the angle of inclination of the original slope on which the clay settled.

Clay will not accumulate on a slope of 30 degrees except as it adheres to the material already there.

Extremely steep slopes may be found on the outer or seaward sides of coral reefs. About some of the islands of the West Indies fault and volcanic slopes of 20° are not uncommon.[8] Some exceed 30°, and several exceed 40°. The steepest slopes formed by deposition are found in the smaller bodies of water where the absence of strong agitation limits wide spreading of material. At the mouth of the Aar where it empties into Lake Brienz the slope of the deposits is 30° near shore and 20° 300 meters from the shore.[9] The delta of the Dundelbach in Lake Lungern has a slope of 32° to 35°. These slopes are to be contrasted with those of the Mississippi and Rhine delta fronts, which average about 1° for the former and about 0.5° for the latter. The angle of deposition must also be considered in connection with the base level of deposition, as the finer materials are swept out over this surface and deposited in deeper water where the inclinations of the bottom are those of the continental slopes or the surface of previous deposits. As these deposits are made in waters which may be little agitated, initial inclinations may be large and are apt to be preserved. The sea bottom adjacent to a coast of submergence may have steep slopes and hence possibilities for high angles of initial inclination. It would seem that the gentlest initial inclinations should be made over the deep ocean bottom and extensive lowlands invaded by the sea. Very flat-lying deposits are also made on river flood plains, lake bottoms, playas, and in other shallow bodies of water.

River channels which are being aggraded are not infrequently filled with sediments which arch downward from bank to bank, giving a synclinal effect. It is not known to what order of magnitude these "synclines" may develop.

Many examples of high initial inclination are known from the geologic column. Mather has described initial inclination of 7° in limestones near Kingston, Ontario, the strata lapping against a granite knoll, and the beds thickening with distance from the knoll so that the higher beds approach horizontality.[10] Mississippian limestones in Allen County, Kentucky, are

[8] See United States hydrographic charts, particularly No. 2318.

[9] Thoulet, J., op. cit., p. 54.

[10] Mather, K. F., Surficial dip of marine limestones, etc., Econ. Geol., vol. 13, 1918, pp. 198–206.

stated to have initial inclinations up to 10°. Shaw has described examples of initial inclination in connection with coal beds and limestones of western Pennsylvania.[11] A coal bed in a mine south of Oakland, Indiana, dips 50 feet in a half mile, whereas an underlying coal bed in the same mine is essentially horizontal. Inclinations of 5° and 6° are common about the Silurian coral reefs of Gotland, Anticosti, and Wisconsin and the upward range is to as great as 40° or more. Very steep inclinations may be found in sand and gravel deposits. On the north side of the Baraboo Range there are places where the Cambrian sandstones and conglomerates dip to the north at angles as great as 15°. Dips up to 25° are not uncommon about the St. Francis Mountains of southeastern Missouri, and dips of 30° have been found in a few places, these dips occurring in rocks ranging from sandstones to dolomites.[12]

Thickness of Units of Stratification

The units of stratification range in thickness from paper-thin in some muds to many feet in these and other sediments. In general, the thickness of most units falls between 2 inches and 2 feet. As noted elsewhere, the thickness of units is not a measure of duration of deposition, as a paper-thin shale or a thin layer of sandstone may have taken a longer time to deposit than many feet of sandstone. Branson[13] has assumed that "extensive thin-bedded deposits could not form by means of subaerial agents, but only in rather quiet waters," but this is an assumption not to be accepted until proved by extensive studies of subaerial deposits in process of formation; and in the same category is his assumption that "it seems impossible that extensive ripple marks could form and be preserved in flowing waters of streams." The first assumption is doubtful, and the latter may be proved incorrect in several deposits.

Causes of Development of Stratification

Stratification appears to develop as a consequence of (1) seasonal changes, (2) weather changes, (3) variations in currents, (4) changes in climate, (5) rise of sea level, (6) deposition of colloidal sediments, (7) and growth of organisms. One of the more difficult problems confronting the sedimentationist is that relating to the origin of stratification, and few criteria have been established which make possible the determination of the origin of this structural feature and the environment in which it developed.

[11] Shaw, E. W., Anomalous dips, Econ. Geol., vol. 13, 1918, pp. 598–610.

[12] Bridge, J., and Dake, C. L., Initial dips peripheral to resurrected hills, Appendix 1, 55th Biennial Rept., Missouri Bureau Geol. and Mines, 1929, pp. 1–7.

[13] Branson, E. B., Triassic-Jurassic "Red Beds" of the Rocky Mountain region, Jour. Geol., vol. 35, 1927, pp. 625–626.

STRATIFICATION DUE TO SEASONAL CHANGES. Seasonal changes may lead to stratification in the deposits of land waters and in those of marine waters directly affected by land conditions. In most regions the rainy season is flood time; the lakes, flood plains, and deltas are then receiving their maximum accumulations. The dry periods are times of low water when the main sites of deposition receive no deposits or thin deposits of fine material. It is probable, therefore, that stratification due to this cause would not develop in marine deposits except in the vicinity of the mouths of rivers.

Shaw has suggested that seasonal stratification is responsible for some of the laminations of the Mississippi Delta sediments.[14] Trowbridge dissents from this suggestion.[15] Gale[16] referred the banding of some of the Alsace potash deposits to seasonal deposition, a thin layer of sodium chloride being deposited in summer and a layer of sylvite of about equal thickness in winter. In this connection there should be mentioned the laminated anhydrite described by Udden from the Permian of Texas, in which the laminations average less than 2 mm. thick and extend essentially without interruption through over 1000 feet of anhydrite. In 13 feet, 1737 laminations were measured. They appear to be arranged in cycles. The significance of the laminations,—whether they represent days, years, or other periods,—has not been determined.[17]

Raymond and Stetson[18] have described the occurrence of a jelly-like substance on the bottom of Massachusetts Bay whose origin, they suggest, is due to the decomposition of eel grass, a seasonal plant. The production of this jelly would come during a limited part of each year, thus giving an annual deposit separated by the deposits of the other part of each year.

Aqueo-glacial deposits, particularly those of lakes, are stated to exhibit seasonal stratification to a marked degree. The rapid melting of summer and the relatively high burden of suspended matter give a deposit of a certain degree of coarseness for a particular place. The deposits of the succeeding winter at the same place are thinner and composed of finer grained materials, these commonly having darker colors than those deposited in summer. The winter band is sharply separated from the summer band above, but grades into the summer band below. Chemically the

[14] Shaw, E. W., The mud-lumps at the mouths of the Mississippi, Prof. Paper 85–B, U. S. Geol. Surv., 1913, p. 17.

[15] Trowbridge, A. C., Rept. of Comm. Sedimentation, Nat. Research Council, 1923, p. 58.

[16] Gale, H. S., The potash deposits of Alsace, Bull. 745B, U. S. Geol. Surv., 1921, p. 48.

[17] Udden, J. A., Laminated anhydrite from Texas, Bull. Geol. Soc. Am., vol. 35, 1924, pp. 347–354.

[18] Raymond, P. E., and Stetson, H. C., A new factor in the transportation and distribution of marine sediments, Science, vol. 73, 1931, pp. 105–106.

summer and winter bands are much alike except that the winter bands contain more ferric oxide, alumina, and potash and somewhat less lime. The winter bands of glacial lakes are assumed to have been deposited when the lakes were frozen over.

In Sweden De Geer,[19] in America De Geer, Antevs,[20] and others, and in Finland Sauramo[21] have used the occurrence of such laminations in estimating the time since glaciation. Sayles has interpreted the lamination in Permian glacial clays near Boston as due to this cause[22] and other laminated clays as suggestive of glaciation.[23] In Australia David and Süssmilch interpreted laminæ of Carboniferous glacial lake deposits as due to seasonal deposition.[24] Johnston's[25] studies of Lake Louise, Alberta, which is fed by Victoria Glacier, indicated a rate of deposition of one-sixth inch per annum. The study of the deposits showed four to six seasonal bands per inch, strongly suggesting that each band represents a year. The thickness of a varve varies, ranging from a few millimeters to several inches and perhaps a foot or more. The summer or winter portion of a varve may be laminated, this arising from variations in melting between day and night, variations in competency of waters reaching a place, and probably other causes.

Studies made by Fraser[26] indicate that the velocity of fall of particles less than 0.5 mm. in diameter decreases with decreasing temperature until a minimum is reached at 4°C., and the retardation of fall above the latter temperature becomes greater as the particles decrease in diameter. The result is a distinct grading, as may be seen in glacial varves. Unflocculated varved clay gave lamination when permitted to settle in fresh water just above freezing, but gave no lamination at 20°C. Experiments show that the maximum salinity permitting formation of varves in coarse clay seems

[19] De Geer, G., A geochronology of the last 12,000 years, Compt. rend., Congr. Géol. Internat., Sess. 11, Stockholm, 1910, 1912, pp. 241–253.

[20] Antevs, E., The recession of the last ice sheet in New England, Am. Geog. Soc., Research Ser., no. 11, 1922.

[21] Sauramo, M., Studies of the Quaternary varve sediments in southern Finland, Bull. Comm. Géol. Finlande, vol. 60, 1923, pp. 1–164.

[22] Sayles, R. W., Seasonal deposition of aqueoglacial sediments, Mem. Mus. Comp. Zool., vol. 47, no. 1, 1919; New interpretation of the Permo-Carboniferous varves at Squantum, Bull. Geol. Soc. Am., vol. 40, 1929, pp. 541–546; see also Wallace, R. C., Varve materials and banded rocks, Trans. Roy. Soc. Canada, vol. 21, 1927, sect. iv, pp. 109–118.

[23] Sayles, R. W., Possible tillite at Levis, Quebec. Abstract, Bull. Geol. Soc. Am., vol. 33, 1922, pp. 99–100.

[24] David, T. W. E., and Süssmilch, C. A., Proc. Roy. Soc. New South Wales, vol. 53, 1919–1920, p. 27.

[25] Johnston, W. A., Sedimentation in Lake Louise, Alberta, Am. Jour. Sci., vol. 4, 1922, pp. 376–386.

[26] Fraser, H. J., An experimental study of varve deposition, Trans. Roy. Soc. Canada, vol. 23, sect. iv, 1929, pp. 49–69; Kindle, E. M., Sedimentation in a glacial lake, Jour. Geol., vol. 38, 1930, pp. 81–87.

to be about one-fiftieth that of normal sea water, thus indicating that typical aqueo-glacial varves are fresh-water phenomena.

Varved gyttjas are composed of sediments consisting largely of organic matter, as animal remains, plants, excrements, etc.[27] Such are now said to be forming in the deeper waters of McKay Lake near Ottawa, the laminations being due to alternations of grayish-white, finely divided lime carbonate, and dark reddish organic matter with traces of lime carbonate,[28] the thickness of two laminæ being about 0.5 mm.

STRATIFICATION DUE TO WEATHER CHANGES. Stratification arising from weather changes would probably be developed wherever sediments are deposited in waters which are not extremely deep. A storm might affect all shallow-water sites of deposition in the region of occurrence, and a different type of sediments would be deposited during and immediately after the storm than before. Vast quantities of sediments might be swept seaward and deposited upon those portions of the bottom which are deeper than the temporary base level of deposition. These deposits would be different from those of the time before the storm.

STRATIFICATION DUE TO CLIMATIC CHANGES. Climatic changes are known to have occurred in many parts of the earth, and as the quantities, compositions, and colors of sediments to a large extent are controlled by climate, each climatic condition should be reflected to a greater or less degree in the stratification. It is probable, however, that climatic changes are never abrupt and require long intervals of time for consummation, thus rendering it essentially impossible that small-scale stratification units could result. Gilbert[29] has appealed to the astronomic cycle of the precession of the equinoxes as a cause of climatic change leading to the deposition of various units in the Colorado Cretaceous. The precessional period causes summer and winter to change places in each hemisphere. As a consequence, the climate might be warm and dry during one period of the reversal of the seasons and during the other moist and cool, with corresponding differences in the sediments derived from or deposited in the regions affected, but as the change takes place gradually it is difficult to see how stratification could be affected. The Bruckner cycle of 35 years might lead to stratification changes.

STRATIFICATION DUE TO VARIATIONS IN CURRENTS. Stratification due

[27] Antevs, E., Retreat of the last ice-sheet in eastern Canada, Mem. 146, Geol. Surv., Canada, 1925, p. 5; Lindquist, G., Notice on varved gyttjas, Geol. Fören. Förhandl., Stockholm, vol. 46, 1924, p. 193.

[28] Whittaker, E. J., Bottom deposits of McKay Lake, Ottawa [Ontario], Trans. Roy. Soc. Canada, vol. 16, 1922, pp. 141–157 (147).

[29] Gilbert, G. K., Sedimentary measurement of Cretaceous time, Jour. Geol., vol. 1895, pp. 121–127.

to variations in currents arises from changes in current direction and competency. Such changes may bring sediments which are different from those of previous deposition. The tides wash into bays, estuaries, etc., and sediment is thrown into suspension, of which much is redeposited over the surface whence it was derived, but parts are carried elsewhere. Stratification results in each locality. Johnston assigns some of the lamination in the Fraser River delta deposits to tidal deposition.[30]

Stratification Related to Rise of Sea Level. Sea bottoms below the profile of equilibrium receive and retain deposits until built to that level. This is a temporary base level of deposition, and when it is reached no further permanent deposit is made over that part of the sea bottom. Any sediments brought to this bottom are shifted back and forth, the finer ultimately being carried to deeper waters. Each rise of sea level permits further deposition on the bottom to a thickness which approximates the rise of sea level, following which the top of the deposit becomes the surface over which sediment is shifted. The top of each stratum deposited under these conditions has a surface developed by current and wave wash, and two strata are separated from each other by a period of no deposition whose duration represents the time between two successive rises of sea level minus the time required to raise the bottom to the profile of equilibrium. This break in deposition, which may, and in many instances does, represent a much longer time than is required to deposit a stratum, has been designated a diastem.[31] It may have the time value of a disconformity. It is considered that rise of sea level may have been responsible for much of the stratification in the Ordovician over and around the Cincinnati Arch, the Ordovician and Silurian limestones of the Michigan Basin, the Ordovician and Silurian of Anticosti, and the Pennsylvanian of the Mid-Continent region. It must, however, be fully appreciated that much stratification of other origin is probably present in each of these regions.

To this cause may be assigned some of the rude stratification occurring in coral-reef rock. The corals build to or adjacent to the surface of the water, and when that level is reached, upward growth ceases until a rise of sea level again makes it possible.

Stratification Due to Organic Growths. Portions of the bottom of water bodies are thickly carpeted with the shells and tests of living organisms which from time to time may be brought to the verge of extinction by changes in the physical conditions, such as an influx of waters of different

[30] Johnston, W. A., The character of the stratification of the sediments in the recent delta of Fraser River, British Columbia, Canada, Jour. Geol., vol. 30, 1922, p. 123.

[31] Barrell, J., Rhythms and the measurement of geologic time, Bull. Geol. Soc. Am., vol. 28, 1917, p. 794.

temperature, too much material in suspension, a change in the chemical content of the water, etc. This leads to a break in accumulation and stratification. Changes in an environment may eliminate certain members of a fauna, or even an entire fauna, and at the same time create a new environment favorable to a different group of organisms. The deposits of each environment might be expressed as a distinct bed.

Stratification of Colloidal Sediments. Very fine particles which are permitted to settle in still water arrange themselves in strata while still in suspension, each stratum being of approximately uniform opacity and the higher less so than those below.[32] Studies made by Mendenhall and Mason, using Cucuracha shale from the Panama Canal region, led to the following conclusions.[33]

1. A lateral temperature gradient produces convection, and several distinct convection systems may develop in a mixture, the number depending on the magnitude of the lateral temperature gradient and the magnitude of the vertical density gradient arising from the settling of the particles.

2. The greater the vertical density gradient, the greater the number of strata produced by a given temperature gradient. If the temperature gradient for a given density gradient is too high, no strata result.

In most waters it is improbable that any stratification will arise from this cause, but possibly in very deep holes in lakes and the sea, the sediments may settle in the order of stratification in suspension, and paper-thin shales develop. However, it is considered improbable that any stratification known in the geologic column owes its origin to this cause.

If certain salts are introduced in a suspension of finely divided matter, a different type of stratification arises. Davis[34] prepared a suspension of finely divided clay in water containing a moderately strong content of sodium silicate. A solution of ammonium carbonate was carefully added so as to avoid serious mixing. Downward diffusion of the ammonium carbonate resulted, with flocculation of silicic acid and the development of alternate bands or laminæ of fine clay and clear gelatinous silica. The laminæ were approximately equally spaced in any one experiment, but with slight variations in different experiments. Some laminæ, both clay and silica, thickened or thinned and terminated lenticularly. The experiment repeated with red shale and powdered crystalline quartz gave like results. Similar results might develop in the sediments of a sea or lake bottom composed of fine mud containing an abundance of organic matter.

[32] Barus, C., Bull. 36, U. S. Geol. Surv., 1886, pp. 15–20; Bull. 60, 1890, pp. 139–145.

[33] Mendenhall, C. E., and Mason, M., The stratified subsidence of fine particles, Proc. Nat. Acad. Sci., vol. 9, 1923, pp. 199–207; Theory of settling of fine particles, Rept. Comm. Sedimentation, Nat. Research Council, 1923, pp. 53–54.

[34] Davis, E. F., The Radiolarian cherts of the Franciscan group, Bull. 11, Univ. California Publ., Dept. Geol., no. 3, 1917, pp. 36, 399–402.

Concentric banding of the kind shown in cherts might arise in the same way. In the Liesegang experiments, glass plates coated with gelatine impregnated with potassium bichromate had a drop of silver nitrate placed upon them. A series of concentric rings formed around the drop, the rings being closely spaced adjacent to the drop and progressively wider apart with distance therefrom. Experiments by Stansfield[35] showed that under certain conditions it is possible to obtain equally spaced rings.

INFLUENCE OF TEMPERATURE ON LAMINATIONS. Work by Kindle[36] has shown that temperature is a factor producing lamination in fine sediments. The substance of his conclusions is as follows.

1. Lamination which resembles that generally assumed to be produced by seasonal deposition is developed by continuous and uninterrupted settling of fine sediments.

2. Temperature is an important factor in modifying the color and physical character of the laminations.

Rhythms in Stratification

Many geologic sections show something of a rhythmic arrangement in the strata, with the rhythms in some cases of several orders. In some sections strata of coarse materials alternate with finer through a greater or lesser sequence, and the alternations may fall into several units of a higher order. In other sections limestones alternate with shales and a group of strata in such arrangement alternate with beds of shale. Or there may be three different varieties of rock with arrangement in rhythmic order. Many chert and other concretionary structures exhibit rhythmic arrangement in their concentric laminæ. The factors responsible for the development of such rhythmic or cyclical arrangement are known in but few cases. Some rhythms no doubt are due to recurrences of chemical or organic conditions, others to recurrences of physical conditions, and still others to alternations of several conditions. The finding of rhythms by geologists seems at the present time to be a pleasant diversion. The first serious consideration of this problem was that of Barrell; others subsequently have made important and valuable contributions.[37] The conditions deemed important in producing rhythms are considered in the following paragraphs.

RHYTHMS DUE TO WEATHER CHANGES. Extensive falls of rain or snow

[35] Stansfield, J., Retarded diffusion and rhythmic precipitation, Am. Jour. Sci., vol. 43, 1917, p. 1.

[36] Kindle, E. M., Rept. Comm. Sedimentation, Nat. Research Council, 1924, pp. 40–42.

[37] Barrell, J., Rhythms and the measurement of geologic time, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 745–904; Weller, J. M., Cyclical sedimentation of the Pennsylvanian Period and its significance, Jour. Geol., vol. 38, 1930, pp. 97–135; Richardson, W. A., Quart. Jour. Geol. Soc., vol. 79, 1923, pp. 96–97.

result in flooded streams, and sediments of a certain degree of coarseness are brought to the flood plains and deltas. The subsiding waters lead to the deposition of finer sediments. Over fresh-water lake bottoms Kindle has shown that the sands settle first from suspension, and subsequently the fine muds. Each storm thus stirring up the bottom of a fresh-water lake makes a thin layer of material of a certain degree of coarseness succeeded by one of finer. In the sea and salt-water lakes the silts and colloids may flocculate and reach the bottom first, and the deposition of coarser material may follow.[38] During storms, sediments of temporary deposition on shallow bottoms may be swept into the deeper waters on the continental slopes in quantities larger than ordinary. These sediments may be coarser than those of previous deposition and may be succeeded by finer deposits laid down during the non-stormy periods. A rhythm thus begins with coarse materials in a relatively thick band and closes with a thinner band of fine material.

Rhythms Due to Seasonal Changes. The spring and early summer seasons of many parts of North America and the world are the times of flood waters, and late summer and autumn the times of low waters. During the former the flood plains and deltas receive deposits of sediments of a certain coarseness; during the latter, no or thinner deposits of greater fineness, the rhythm thus beginning with coarser materials succeeded by finer. Each seasonal rhythm may also include several rhythms due to weather conditions. On bottoms deeper than the profile of equilibrium there is a maximum of deposition during those seasons of the year characterized by many storms and much rough weather. The intervening seasons of few storms are indicated by deposition of finer sediments of less thickness.

In glacio-fluvial and glacio-lacustrine deposits the times of warmth are the times of melting and abundance of waters; the periods of cold are those of little melting and little water. During the former the waters of the streams may be turbid, and the material deposited at any place has a certain coarseness; during the latter the streams and lakes may be ice-covered, the waters are clearer, and the deposits at the place are of finer grain. In very fine-grained sediments of this origin the smallest rhythm may be the annual one. In coarser sediments it might be possible to develop a rhythm each day, groups of diurnal rhythms forming the one of seasonal origin. Raymond and Stetson[39] record the occurrence of a jelly-like substance over parts of the bottom of Massachusetts Bay and, following Petersen,[40] sug-

[38] Kindle, E. M., Diagnostic characteristics of marine clastics, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 907–908.

[39] Raymond, P. E., and Stetson, H. C., A new factor in the transportation and distribution of marine sediments, Science, vol. 73, 1931, pp. 105–106.

[40] Petersen, C. G. J., Rept. Danish Biol. Station, vol. 20, 1911.

gest that this represents decomposed eel grass, a seasonal plant. The seasonal growth would produce an annual deposit of "jelly" and thus give rise to a rhythm which might resemble a varve.

Stamp[41] has described rhythmic arrangement of laminated sediments in the Tertiary of Burma, which arrangement he assigns to "an annual variation in the volume and carrying capacity of the river or rivers which were sweeping sediment into the Burmese Gulf." The annual deposit is stated to consist of a double lamina, of which the coarser portion was deposited during the high-water or flood season, and the finer portion during the low-water season. While the above may be the correct explanation, it does not seem that other possible explanations have been eliminated. Rubey[42] has suggested that pairs of laminæ in the Cretaceous shales of the Black Hills region may represent seasonal deposition.

Rhythms Due to Climatic Changes. The best known of the climatic and astronomic cycles are the 35-year cycle of Bruckner, the 21,000-year cycle of the precession of the equinoxes, and the 91,000-year cycle of minimum and maximum eccentricity. The repeated occurrence of glaciation during geologic time suggests others. It is not known what climatic cycles may do in sedimentation. It is possible that during one half of the cycle sediments of certain characteristics are deposited, and sediments of other characteristics during the other half. As mentioned before, Gilbert thought that the precessional cycle might have been responsible for the rhythmic arrangement of some of the units of the Cretaceous sediments of Colorado, wherein the sequence consists of 3,900 feet of shales and limestones, the latter constituting only a small part of the whole. The rhythms are best shown in the Benton, the base of the Niobrara, 90 feet above the base of the Niobrara, and at the top of the Niobrara. Each cycle is represented by from 18 inches to 3 feet of limestone and shale.[43]

Barrell has described ribboned slates at Slatedale, Pennsylvania, in which rhythms of great regularity are shown by thick bands of dark slates separated by thinner bands of light shales, the latter containing considerable sand. As the deposits have wide extent, are extremely fine, and contain an abundance of carbon, slowness of deposition is suggested. The sandy layers may indicate stirring up of the bottom and the washing away of the finer

[41] Stamp, L. D., Seasonal rhythm in the Tertiary sediments of Burma, Geol. Mag., vol. 62, 1925, pp. 515–528.

[42] Rubey, W. W., Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills Region, Prof. Paper, 165–A, U. S. Geol. Surv., 1930, pp. 40–44; Possible varves in marine Cretaceous shale in Wyoming, Abstract, Jour. Washington Acad. Sci., vol. 18, 1928, pp. 260–262.

[43] Gilbert, G. K., Sedimentary measurement of Cretaceous time, Jour. Geol., vol. 3, 1895, pp. 121–127.

materials. Barrell suggested that each rhythm represented a period of years of quiet weather following one of storm, the duration of the cycle not being determinable.[44]

RHYTHMS DUE TO MOVEMENT OF SEA LEVEL. A rise of sea level leads to an invasion of the sea over the land. Sediments of a certain degree of coarseness are then deposited over a given place. With progress inland the place receives finer materials and with still further progress only pelagic sediments may be deposited. If the sea retreats before the bottom is built to the base level of deposition determined by the conditions, muds may be deposited over the pelagic sediments, and over these may be spread sands. The cycle may exist in mixed continental and marine deposits, as those described by Udden[45] and Weller[46] from Illinois, the ascending sequence in the cycle consisting of (1) sandstones and sandy shales, (2) under clay, (3) coal, and (4) marine limestones and shales, the cycle having an unconformity at the base indicating, according to Weller, uplift and erosion followed by submergence. The deposits seem to be those of the delta environment, and it is possible that the cycle does not always indicate uplift, but that in some cases periodical subsidence only took place. Weller gives the following succession as that of a typical Illinois Pennsylvanian formation:

Marine
- 8 Shale, containing ironstone bands in the upper part and thin limestone layers in the lower part.
- 7 Limestone.
- 6 Calcareous shale.
- 5 Black shale

Continental
- 4 Coal.
- 3 Underclay, not uncommonly containing concretionary or bedded fresh-water limestone.
- 2 Sandy and micaceous shale.
- 1 Sandstone.

Unconformity.

The unconformity is not necessarily that of land erosion due to uplift. If the continental deposits are those of the delta environment, the unconformity may have been developed through the building of the delta over a bottom that had reached the base level of deposition for the conditions, and thus presented an eroded surface for the continental deposits, the channels

[44] Barrell, J., Rhythms and the measurement of geologic time, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 803–804.

[45] Udden, J. A., Geology and mineral resources of the Peoria Quadrangle, Bull. 506, U. S. Geol. Surv., 1912, pp. 47–50.

[46] Weller, J. M., Cyclical sedimentation of the Pennsylvanian Period and its significance, Jour. Geol., vol. 38, 1930, pp. 97–135.

representing places where the extended streams cut into marine deposits. Where a considerable extent of marine deposits has been eroded, uplift seems to be implied. Moore[47] describes a cycle from the Mid-Continent Pennsylvanian which in ascending order when completely developed consists of (1)

limestone, yellowish brown, massive, locally irregular and impure, about 5 to 10 feet; (2) shale, clayey to calcareous, bluish, gray or yellowish, 5 to 15 feet or more; (3) limestone, blue, very hard, dense, brittle, a single massive bed weathering in angular blocks, thickness never more than 2 feet; (4) shale, dark bluish and black, fissile, clayey, the black zone always occurring at the base, 3 to 8 feet; (5) limestone, light gray, thin and unevenly bedded, in some cases chert-bearing, generally 10 to 20 feet thick.

The cyclic sequences are best developed in the Douglas and Shawnee groups of Kansas. The strata concerned seem to be mainly marine, but they are in close association with strata of the continental environment. They seem best interpreted as due to intermittent subsidence.

A rhythm due to movement of sea level may extend through hundreds and even thousands of feet and may include rhythms due to climatic, seasonal, and weather changes, as well as rhythms caused by minor movements of sea level. The large rhythms were designated circles of deposition by Newberry.[48] Cycles of sedimentation described by Stamp[49] in the Eocene of the London and Paris basins are defined as resulting from a transgressing sea and as beginning with a basal conglomerate, progressively younger landward, succeeded seawardly and vertically by sand and clays, and these last in some places by lacustrine, lagoonal, fluvial, and even by eolian deposits. Filling of the basin or retreat of the sea may lead to the deposition of coarse sediments at the summit of the succession. Advance of the sea for the second cycle would remove some of the materials of the preceding, giving rise to an unconformity or "ravinement,"[50] the period between two successive "ravinements" constituting a cycle of sedimentation, the deposits of which record a complete oscillation of a basin, "each oscillation including a positive phase of marine invasion and a negative phase of regression." Figure 73 shows cycles in the Hampshire basin. The Eocene deposits in the Hampshire Basin become more continental toward the west.

If an advance of the sea is pulsatory and the sea bottom is built to the profile of equilibrium before the beginning of each advance, rhythms of a

[47] Moore, R. C., Sedimentation cycles in the Pennsylvanian of the northern Mid-Continent region, Abstract, Bull. Geol. Soc. Am., vol. 41, 1931, pp. 51–52.

[48] Newberry, J. S., Circles of deposition in American sedimentary rocks, Proc. Am. Assoc. Adv. Sci., vol. 22, 1872, pp. 185–196.

[49] Stamp, L. D., On cycles of sedimentation in the Eocene strata of the Anglo-Franco-Belgian Basin, Geol. Mag., vol. 58, 1921, pp. 108–114, 146–157, 194–200.

[50] Stamp designates an unconformity of this origin a "ravinement."

minor order develop. The new rise of sea level brings the bottom below the profile of equilibrium, to which it is built during the time of stability, the bottom then receiving no permanent deposits until sea level rises again. The rhythm consists of various marine sediments succeeded by much washed sediments of indirect stratification. Calcareous sediments may be deposited in clearer but deeper waters, but as the coincidence of the bottom and the profile of equilibrium extends outward, these calcareous sediments become progressively covered on the landward margin with sands or muds, a rhythmic arrangement resulting.

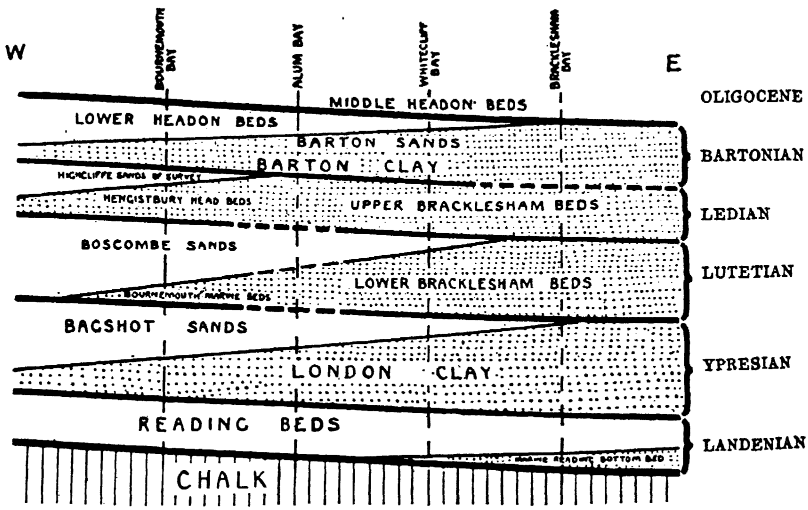


FIG. 73. DIAGRAM OF CYCLES OF SEDIMENTATION IN THE EOCENE OF THE HAMPSHIRE BASIN, ENGLAND

Marine strata are shown on the right, continental on the left. Each marine stratigraphic unit has its initial deposits and final deposits of more or less different character from those above the base and beneath the top. The lines bounding the marine units show the migrations of the shore. The vertical lines show the sections or geograms at the places indicated. Each cycle begins and terminates with a "ravinement." After Stamp, op. cit., 1921. Stamp also shows diagrams of cycles of sedimentation for the Paris, London, and Belgium basins.

SUMMARY. The rhythmic arrangement of sedimentary materials has been observed for more than a hundred years, and that it is a phenomenon of importance is obvious. It is thought, however, that caution is essential in its interpretation. Most sedimentary deposits are not easily studied in three dimensions. It is possible and even probable that if a group of sedimentary units were seen in three dimensions, their rhythmic arrangement would not be so obvious. On the other hand, wide observation is essential to establish such rhythms as those described by Stamp. At the present

time it seems fashionable to discover rhythms, and the writer has the feeling that some of those which have been identified should be accepted with reserve.

CROSS-LAMINATION

Cross-lamination[51] (cross bedding, false bedding) is commonly present in sands and consists of their arrangement in parallel laminæ transverse to the planes of general stratification, the latter commonly truncating the upper edges of the laminæ. At the base the laminæ approach parallelism to the stratification planes, but this may not be very obvious and may not be present in coarse sediments. The tangential termination of the lower ends of the laminæ is known as the bottomset portion, and it ordinarily is composed of material somewhat finer than the inclined or foreset portion. If there are tangential terminations at the tops of the laminations, these are known as the topset portions. The angles of inclination may vary in direction and magnitude. According to Thoulet,[52] the angle of inclination never exceeds 41°. Cressey[53] found that the lee slopes of the dunes on the east shores of Lake Michigan have a maximum slope of 32°. An average high angle of inclination is around 20°. Cross-lamination inclinations are related to the quantity and coarseness of material and the rates of deposition, being steeper under conditions of rapid deposition and in coarse sediments. Initial angles of deposition may be reduced in compacting, although such reduction cannot be very great in sands. Length of foresets, or length of the inclined portion of a lamina, depends on quantity of material, rate of deposition, velocity of current, and other agitation of the medium of deposition. Large supplies and slow currents give steep foresets which are also long. Small supplies and slow currents yield short and steep foresets. Rapid currents and small supplies tend to give long and gently inclined foresets. Extremely long and steep foresets are very common in certain of the Cambrian sandstones of the upper Mississippi valley, some extending 50 or more feet at inclinations of 15° to 20°.

A variety designated festoon cross-lamination has been described by Knight[54] from the Casper and Fountain sandstones of Wyoming which is

[51] Gilbert, G. K., Ripple marks and cross-bedding, Bull. Geol. Soc. Am., vol. 10, 1899, pp. 135–139; Grabau, A. W., Types of cross-bedding and their stratigraphic significance, Science, vol. 25, 1907, pp. 295–296; Andrée, K., Wesen, Ursachen und Arten der Schichtung, Geol. Rundschau, Bd. 6, 1915, pp. 384–395.

[52] Thoulet, J., Ann. Chim. et Phys., vol. 12, 1887, pp. 33–64.

[53] Cressey, G. B., The Indiana sand dunes and shore lines of the Lake Michigan Basin, 1928, p. 38.

[54] Knight, S. H., Festoon cross-lamination, Abstract, Bull. Geol. Soc. Am., vol. 41, 1930, p. 86; The Fountain and the Casper formations of the Laramie Basin, Univ. Wyoming Publ. in Science, Geology, vol. 1, 1929, pp. 1–82 (56–74).

stated "to be the result of: (1) the erosion of plunging troughs having the shape of a quadrant of an elongate ellipsoid; (2) the filling of the troughs by sets of thin laminæ conforming in general to the shape of the trough floors; (3) the partial destruction of the filling laminæ by subsequent erosion, producing younger troughs" which in turn are filled by sets of thin laminæ. The direction of inclination of laminæ is controlled by the direction of plunge of the troughs within which they lie, and in any given trough there is some variation in direction. Inclinations range to 35°, most being between 10° and 25°. The troughs range in depth from 1 to 100 feet, in width from 5 to 1000 feet, and in length from 50 to several thousand feet. The average maximum slope of the sides of the troughs is between 10° and 15°, but may reach 25°. The upper end of a trough is closed, and the angle of inclination becomes or approaches zero at its lower end, where it may terminate at the closed end of another trough. The troughs have a rather constant plunge to the southwest. Many laminæ are stated to be intensely crumpled locally, due to slumping while deposition was in progress. The cross-lamination possesses some of the characteristics of eolian origin, but the constant direction of plunge to the troughs seems to preclude that origin. Knight refers the troughs to development in marine waters through agency of currents and waves produced by tides or storms.

Aside from significance as a sedimentary structure, cross-lamination is important in structural geology, as the truncation at the top of the foresets gives a nearly unfailing means for determination of the tops of beds. If there is no truncation of the upper parts of laminæ, each lamination is an S-shaped curve, but if truncation has occurred, there is a simple curve concave upward. This will aid in determination of position of strata.

Cross-lamination develops under four general conditions or environments not sharply separated from one another: building of deltas and alluvial fans, outward building of the bottom in seas and lakes to the position of the profile of equilibrium, movement of sandbars and dunes, and formation of ripple marks.

Cross-Lamination in Deltas and Alluvial Fans

The cross-lamination in deltas and alluvial fans may have extremely long foresets. The directions of inclinations fan out from the distributaries, the inclination directions extending through an arc of 180° or more. There may be a little cross-lamination in the opposite direction. Cross-lamination strictly due to delta building can be beautifully developed in laboratory experiment, and it probably takes place in small lakes to an almost equally perfect degree, but on large deltas and alluvial fans it is unlikely that cross-lamination due solely to the environment develops. Likewise, it should

be noticed that cross-lamination due to sandbars and ripple mark forms in the delta and alluvial fan environments, this cross-lamination not being differentiable from that similarly formed elsewhere except that its distribution should indicate something of the environment.

Cross-Lamination Resulting from Outward Building of the Bottom in Seas and Lakes

The materials transported outward from shallow-water bottoms by waves and currents extend the shallows into deeper water, and where this has been seen in shallow water, cross-lamination in some cases develops, the directions of inclination being normal to the coast and toward the deeper water.

Cross-Lamination from Movement of Sandbars and Dunes

Sandbars move over bottoms of water as plateau-like areas with steep slopes on the advancing sides. They may range in height from less than an inch to 10 or more feet, most of them being a foot or less. The sand is rolled over the top, which usually undergoes some erosion. Reaching the edge of the plateau, the sands roll down the slope at the front. The direction of the front slope is usually not constant and the inclinations have a similar range in direction. The top surface approximates horizontality, and the bar may rest on a similar surface, but this under surface may have great irregularity due to variations in thickness of deposits and to contemporaneous erosion. These surfaces may be 20 or more feet apart, but more often they are a foot or less. The foresets thus vary in length depending upon the distances separating the bounding planes and the inclinations. Each bed thus formed has its cross-lamination in one direction, which may or may not be the same as that of the beds below and above. Cross-lamination formed in streams has a downstream component from which the direction of stream flow may be determined, but because of meandering the direction of this component may range through every point of the compass. Streams in which tidal action occurs may have cross-lamination with inclination upstream. Cross-lamination in the bars formed in standing bodies of water may have a different direction of inclination in every bed. The shore currents of a coast may have a prevailing, but not constant, direction, sometimes flowing directly opposite to that of the previous day or hour. On other days offshore or onshore currents may incline the lamination away or to the shores.

In general, cross-lamination formed through movement of bars is bounded by parallel planes, the two planes bounding a unit approximating the horizontal. However, either surface may be extremely irregular and very choppy, and violent waters lead to great irregularities in cross-laminations.

Waters of this character may be seen in rivers, estuaries, and over coastal shallow bottoms nearly everywhere.

Dune cross-lamination is developed through deposition on the lee sides at inclinations determined by the nature and quantity of the materials and the rates of deposition. The foresets are likely to be long and almost invariably truncated at the top. Due to the considerable range in direction of winds over short periods, there is great range in direction of inclination of the cross-lamination, and this range is increased because the lee side of

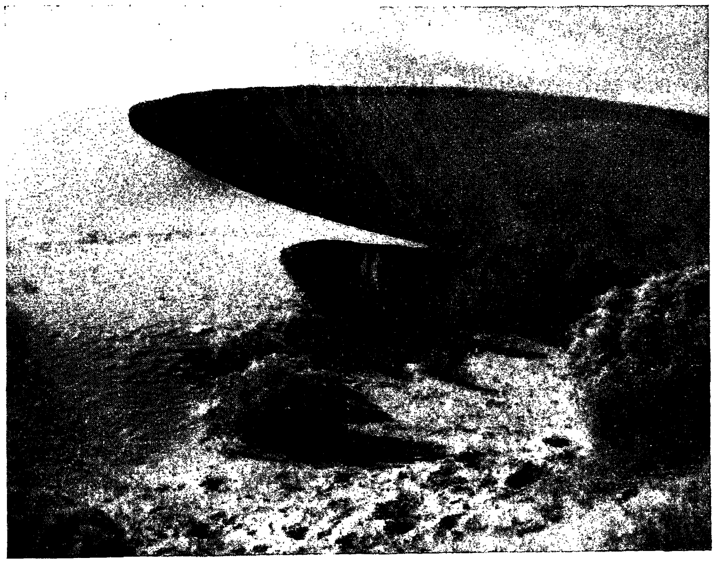


FIG. 74. A CRESCENT-SHAPED DUNE IN THE EASTERN PART OF THE STATE OF WASHINGTON

The lamination will be parallel, in general, to the steep face, but some may be developed on the windward slopes if it becomes necessary to build these to a level required by the competency of the wind. Photograph made by Professor H. E. Culver.

a dune is so frequently irregular in its inclinations, and in the barchane variety of dune the inclinations may have a range through about 180° (fig. 74). The upper bounding plane of dune cross-lamination is inclined, and the lower may be, the cross-laminated unit thus being wedge-shaped in cross section (fig. 75). This and the great variation in direction in any cross-laminated unit seem the only characteristics which differentiate eolian from aqueous cross-lamination, and these are not always certain, as wedge-shaped units may under some conditions develop in water, and considerable variation in direction of inclination may develop under aqueous conditions.

Nevertheless, consistent inclination in any direction would seem to prove aqueous origin. There seem to be no differences in the range of inclination of the laminæ, and each seems to have the same range in length and shape of foresets as the latter are seen in cross section. However, the average

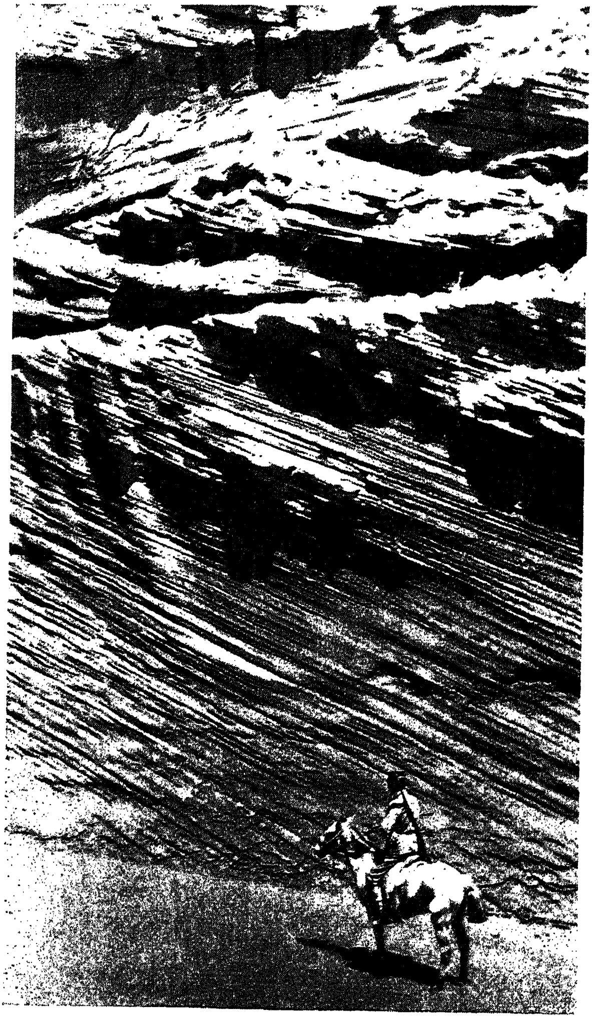


FIG. 75. CROSS-LAMINATION IN THE MESOZOIC RED SANDSTONES NEAR THE SOURCE OF THE YEN-SHUI, NORTHERN SHENSI PROVINCE, CHINA

The lamination shown in the photograph has the characteristics developed by wind. Photograph by E. L. Estabrook, given to the author by F. C. Clapp.

length of foresets of eolian cross-lamination seems longer than in those of aqueous origin, the latter rarely exceeding 2 to 3 feet, the former commonly exceeding those figures, but ranging as high as that of any eolian origin.

Cross-Lamination Made by Ripple Mark

The foresets of cross-lamination made by ripple mark range in length from 3 to 5 inches for the average of those made in water. Ripples made in air have the foresets extremely short, probably less than an inch for most of them. The laminations are made on the lee sides of the asymmetrical ripples and their upper ends are truncated with ripple advance. The cross-lamination of the antidune of water traction is not apparent in those studied in the Sedimentation Laboratory of the University of Wisconsin. It is doubtful if such stand much chance of preservation. The direction of cross-lamination made in ripples records the directions of the currents, the inclinations in all cases except those of antidunes and rapid deposition being in the directions of current movement. As winds vary in direction through all points of the compass, it follows that the inclinations of laminations in wind ripples vary accordingly. Current ripples made in streams have the laminations inclined quite generally downstream, although inclination upstream may take place, particularly in streams affected by tides. Current ripples made in standing bodies of water have inclinations ranging in many directions, but as many currents parallel the shore, inclinations parallel thereto should be common.

Spurr has described an example of apparent cross-lamination in connection with current ripples which is thought to have developed wholly through deposition, no erosion occurring on the currentward side, each new lamination being deposited on the preceding so that the ripples maintained stationary position through several feet of sands. As the sands in the troughs of ripples are different from those on the crests, these different portions became superimposed over one another, and as the axial planes of current ripple marks are inclined upstream, there was thus given the appearance of upstream inclination of cross-lamination.[55] A similar occurrence has been seen in a delta kame near Madison, Wisconsin, and figure 76 shows an example from the Colorado River near the Boulder Dam project.

The cross-lamination in symmetrical or wave ripples is parallel to the surfaces of the ripples, and the inclinations may incline in opposite directions from the crests. Laminæ parallel to one side of a ripple are likely to terminate on the other side of the same ripple. Cross-lamination due to wave ripple is not particularly common.

[55] Spurr, J. E., False bedding in stratified drift deposits, Am. Geol., vol. 13, 1894, pp. 43–47.

FIG. 76. SUPERIMPOSED CURRENT RIPPLE MARKS SHOWING FALSE CROSS-LAMINATION UP-CURRENT

The lower part of the picture shows a surface of deposition. Beyond this are small cliffs or slopes which show the deposit in the vertical dimension and the apparent dip in places of the cross-lamination up-current. The background of the picture shows the wall of Black Canyon. It should be noted that the cross-lamination of the ripples due to rapid deposition is both upstream and downstream. The current was moving to the left. Black Canyon of Colorado River near Boulder Dam. Photograph by Professor W. J. Mead.

UNCONFORMITIES

An unconformity represents a break in the geologic sequence and is a surface of erosion or non-deposition separating two groups of strata. If the strata below an unconformity are not parallel to those above, it is a nonconformity.[56] In general, a nonconformity indicates subaerial erosion preceded by deformation, but it is conceivable that such might also be developed beneath the water if the deformation was such as not to bring the bottom above the surface of the water, but near enough thereto to permit submarine erosion. Apparent nonconformities arise from variations in bedding inclination. An unconformity separating strata which are nearly parallel is a disconformity,[57] and represents a break in the geologic sequence of formation value. A diastem indicates a break of less magnitude than a disconformity and is represented elsewhere by a part of a formation.[58] It follows that there are diastems of many time values and all gradations between disconformities and diastems. A term used in Europe for a variety of disconformity is "ravinement," which is defined by Stamp[59] as "an irregular junction which marks a break in sedimentation. The break may be due to a period of denudation consequent on movement of masses of water, but not necessarily accompanied by earth-movements." Ravinements should be common in deltas and marine shallow-water deposits.

The absence of a break in a sequence implies, and is a consequence of, continuous deposition. Deposition in shallow waters probably is continuous for only brief intervals, and interruption seems to be the normal and usual fact, such interruption ranging from brief cessation of deposition to intervals of many years, and at the upper limit to erosion or the reverse of deposition.

The time value of an unconformity may range from that necessary to deposit a single formation, to such an enormous period of time as that represented by the unconformity between the Pre-Cambrian and Pleistocene. Nor is that the limit, as deposits of the far distant future may come to rest on a Pre-Cambrian surface to give an unconformity of far greater time magnitude. Every unconformity, either directly, or through another unconformity, has connection with the present land surface, and this surface on the oldest rocks may be compared to a low, wide-spreading plant with fan-like branches intercalated in all directions in the surrounding later sedimentary materials, eventually passing into diastems which presumably terminate

[56] Pirsson, L. V., and Schuchert, C., Text-book of geology, 1920, pt. i, p. 311.

[57] Grabau, A. W., Physical character and history of some New York formations, Science, vol. 22, 1905, p. 534.

[58] Barrell, J., Rhythms and the measurement of geologic time, Bull. Geol. Soc. Am., vol. 28, 1917, p. 794.

[59] Stamp, L. D., On cycles of sedimentation in the Eocene strata of the Anglo-Franco-Belgian basin, Geol. Mag., vol. 58, 1921, p. 109.

in the assumed continuous deposits of the deep sea, the unconformity having a different time value at different places.[60]

Disconformities are extremely difficult of determination, particularly after a surface has been brought to minor relief. There seem to be no criteria other than fossils to establish their magnitude. Many important ones long failed of determination, and it is probable that many still remain undiscovered.

Stephenson[61] lists several criteria which may be useful aids in recognition of disconformities. These are as follows:

1. A thin conglomerate composed of pebbles, bones, teeth, or other hard objects at the base of the overlying formation.

2. A thin layer of phosphatic nodules or phosphatic fossil casts of organisms.

3. A phosphatic layer which includes materials obviously derived from an older formation.

4. Sharp differences in lithology of the materials below and above the contact between two strata.

5. An uneven or undulating contact which cuts across the bedding planes.

6. Presence of distinctive faunal zones above and below a contact, which zones are elsewhere known to be separated by other strata of greater or less thickness.

7. Discordance of dip above and below a contact. Rarely determinable in disconformities.

8. Borings made by littoral organisms in strata below a contact, these borings filled with material like that composing the stratum above the contact. An additional criterion would be the occurrence in place of such littoral organisms as barnacles.

While important, only one of the above criteria is definite, as each feature may occur without indicating a disconformity. Number 8, after it had been proved that littoral organisms in place or their structures were present, would prove a disconformity. The best that may be said is that the existence of the features enumerated above suggests a disconformity or a diastem.

Unconformities are here considered from the points of view of occurrence between strata of (1) continental and (2) marine origin. Included with the latter are those unconformities separating marine strata above from rocks of other origin below.

[60] Blackwelder, E., The valuation of unconformities, Jour. Geol., vol. 17, 1909, pp. 289–299.

[61] Stephenson, L. W., Unconformities in Upper Cretaceous series of Texas, Bull. Am. Assoc. Pet. Geol., vol. 13, 1929, pp. 1323–1334.

Unconformities in Continental Sediments

Unconformities developed in continental deposits may occur in connection with fluvial, lacustrine, paludal, deltaic, glacial, and eolian sediments. Unconformities in fluvial, lacustrine, paludal, and deltaic sediments are considered under the head of fluvial sediments.

Unconformities in fluvial sediments may be examined from four points of view, as follows: (1) unconformities arising in channel deposits with the stream maintaining a constant position, (2) unconformities arising through the migrations of an aggrading stream over its deposits, (3) unconformities developed in the deposits of streams which alternately aggrade and degrade, and (4) unconformities developed through growth of alluvial fans and deltas.

1. Every stream scours and fills, the former occurring at flood time in the deeps and at low water on the shoals, the filling taking place in the opposite sense. In the deposits thus formed, a limited section might show unconformable relationships with relief as great as 50 or more feet, and if a section parallel to the course of a channel could be observed, the unconformity might be traced for long distances. As many unconformities would be present in such channel deposits, the correlation of those exposed in different sections would be difficult. The high initial dips might suggest nonconformity. The time interval represented by an unconformity developed in this manner usually is not long, and the magnitude of the break is that of a diastem.

2. A stream forming a flood plain of construction, or an alluvial fan, at one time or another occupies nearly every place on its flood plain. This is done by the migration of meanders and by the stream breaking through its natural levees and seeking the lower land of its back swamps. In the migration of the meanders, cutting is done on the convex side of the current and deposits are made on the concave side, these resting on a stream-eroded surface with irregularities inherent to the method of development. If a stream breaks through its levees, its new channel is cut in earlier deposits, and the fillings in this channel will have unconformable relationships to those beneath. As a flood plain or alluvial fan may contain river lakes and swamps, the unconformable relationships may be between lake, swamp, and river sediments below and river sediments above, or in the opposite sense. It is thought that an unconformity of this origin may have a relief as great as 50 feet and be traceable for many miles. The high initial dips might suggest a nonconformity. The interval may equal that of a disconformity or a diastem.

3. An aggrading stream ultimately reaches a stage where a profile of equilibrium is attained, and deposition ceases so far as raising the surface

is concerned, but the stream continues to migrate over the surface of its flood plain, and there may be gradual lowering of the surface. An increase in the supply of sediments, a downwarping of the flood plain, or a change in the climate of the flood plain to drier conditions may restore aggradation, and the deposits then made would lie unconformably on those below. The time interval represented by this disconformity may be long, and the high angles of initial dip may suggest nonconformity.

4. Alluvial-fan and kindred deposits by progressive overlap over the region on which they form develop an unconformity between themselves and the rocks beneath. The time interval may be very long and the relations those of nonconformity or disconformity.

The delta environment represents conditions similar to those of flood plains, but because of nearness to the sea another factor enters. A delta exists because of dominance of stream supply of sediments over wave and current disposition. Stream supply varies with climatic and topographic conditions at the sources. If these vary sufficiently widely and the stream at any time brings less sediments than the waves and currents are able to handle, the latter may remove a part of the materials at the delta front and develop a surface of erosion in so doing, and this may continue until the entire surface of the delta has been traversed. If the supply of sediment later rises above the disposing ability of the waves and currents, the delta advances and new deposits are made upon an eroded surface. A disconformity results. It may separate fluvial, paludal, and lacustrine deposits, and the time interval may be long. The advance of a delta over a marine bottom built or eroded to the profile of equilibrium places the delta sediments in disconformable relationships to the marine sediments beneath.

Glaciers advance and retreat, and each advance may erode the surface. During each retreat this surface receives glacial and aqueo-glacial deposits. A unconformity results which in some places appears as a disconformity and in others as a nonconformity. For an unconformity of this type of wide distribution the time interval may be long.

Winds frequently erode previous deposits, and subsequently they may make a deposit on the eroded surface, the breaks being in the nature of diastems.

Speaking generally, it needs to be emphasized that estimates of the time values of unconformities in continental deposits have little merit unless the estimates are strongly supported by fossil evidence of unquestioned character. The relief has little significance, as it may range from nothing to 50 or more feet in a limited exposure.

Unconformities Connected with Marine Sediments

Unconformities connected with marine sediments are arranged in five groups. These are not designated by name, but are discussed in succeeding paragraphs.

1. Rapid rise of sea level over a land of considerable relief advances a shore in landward direction, each successive deposit extending farther on the land and giving the marine progressive overlap of Grabau.[62] The submerged surface may be quickly brought beneath the level of the profile of equilibrium and thus experience little marine erosion. The relations may be those of nonconformity or disconformity; the relief of the surface may be great; and the time is quite certain to be long. Rapid rise of sea level over steep slopes favors the development of a basal conglomerate.

Such an unconformity has sediments nearest the original shore with characters determined by the conditions, and these would be followed seaward by others with characters of greater or less differences. With advance of the waters over the previous land surface, the shoreward and succeeding sediments follow, at the same time rising stratigraphically, being youngest in that part of the region marking the maximum progress of invasion. According to Hill,[63] the Edwards limestone of the Texas Comanche series and the Austin chalk of the Gulf series thus transgress time diagonally, the former being higher westward from Austin and the latter rising eastward from Texas. Stamp[64] has called attention to an interesting case in the Tertiary of Burma (fig. 77) in which "paleontological stages cross the lithological horizons" in a very marked way. It is not certain whether the paleontological stages or the lithological horizons represent definite time units. Cases of diagonal transgression of time should be the rule in overlap, but few have been noted.

2. Slow rise of sea level may permit a wave-cut surface on solid rock for a long distance from shore; the place of permanent deposition is also a long distance thereform; thus the sediments are likely to be fine, and, ultimately, as the wave-eroded surface sinks below the level of the profile of equilibrium, it becomes covered with fine-grained terrigenous sediments or some type of pelagic sediments. A land surface in the late-maturity or old-age stage of the cycle of erosion would be likely to have a high water table and prob-

[62] Grabau, A. W., Principles of stratigraphy, 1913, p. 723.

[63] Hill, R. T., Two limestone formations of the Cretaceous of Texas which transgress time diagonally, Science, vol. 53, 1921, pp. 190–191.

[64] Stamp, L. D., Seasonal rhythm in the Tertiary sediments of Burma, Geol. Mag., vol. 62, 1925, pp. 515–528, fig. 2; The geology of the oil fields of Burma, Bull. Am. Assoc. Pet. Geol., vol. 11, 1927, pp. 557–579, fig. 6.

ably a shallow depth of decay, so that as the sea advanced over the land there would have been little undecomposed rock to remove, and the wave-cut profile would also be built on solid rock as above, the surfaces in either case having little relief. Unconformities of this character seem common in the geologic column, as shown by the rather general occurrences of undecomposed rock surfaces of little relief at the base of marine sequences. The relations may be disconformable or nonconformable, and basal conglomerates are not probable. The relief of the unconformity is dependent on the character of the original land surface and the rate of rise of sea level, being least for slow rise of sea level and low elevations. The time interval is long.

A modification of this type of unconformity exists in those cases where the rise of sea level is interrupted by times of stability. If these times of

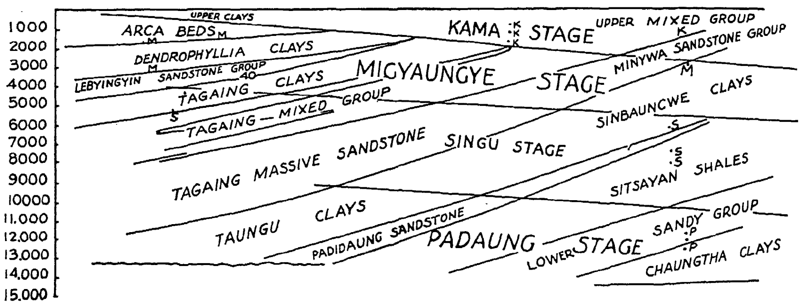


FIG. 77. NORTHWEST TO SOUTHEAST DIAGRAMMATIC SECTION OF THE UPPER PUGUAN REGION OF CENTRAL BURMA

About 30 miles are shown, the lithic units rising to the southeast, the faunal units to the northwest. The diagram shows the lack of coincidence of the faunal and lithic units, or their diachronous behavior. After Stamp, L. D., Bull. Am. Assoc. Pet. Geol., vol. 11, 1927, p. 566.

stability are longer than required to build the bottom at a given place to the level of the profile of equilibrium, the excess time will have no representation at this place other than a thin, much worked over deposit from which the finer materials have been removed. Remains of animals and plants that lived on this bottom while it was at the depth of the profile of equilibrium are not likely to be preserved, as solution, abrasion, and scavengers would have destroyed them. The unconformity of erosion on the submerged land surface thus merges seaward into a disconformity or diastem of non-deposition. It seems probable that many unconformities of this character occur, though they have rarely been recognized.

A somewhat similar condition obtains as a consequence of the marine cycle (fig. 3). In the early stages of the cycle the bottom receives certain quantities of sediments and may be built up to the profile of equilibrium

determined by the conditions. As the cycle progresses toward completion, the quantity of sediments decreases and ultimately may become very small, determining a lower profile of equilibrium and making necessary the removal of some of the sediments previously deposited. A submarine erosion surface results on which rests a veneer of the coarser particles washed from the removed sediments.[65] The beginning of a new cycle covers this surface with sediments, and the unconformity over the submerged land thus passes into one developed beneath the sea. Every period of the past that witnessed stable conditions for a long time and was followed by submergence should have unconformities of this kind in its rocks.

3. Rapid falls of sea level bring parts of the bottoms above the profile of equilibrium, and sediments will be removed from such parts, leaving an eroded surface on which permanent deposits are not made until there is a rise of sea level or an increase in the supply of material. Such deposits, when made, hold disconformable relationships to those beneath. The disconformity or diastem is likely to have little relief, may represent a short or a long time, and as a rule is not indicated by a basal conglomerate, though the basal materials may be coarser than those which follow. Few remains of the organisms dwelling on the bottom during either the deposition or erosion of the missing strata will be present in the basal layer because of scavengers, solution, and wave action.

4. The profile of equilibrium established on any water body bottom is not entirely dependent on local conditions, but to a considerable extent is influenced by outside conditions. As the latter change, a lower or higher level may be established and the bottom may be eroded or receive deposits, a stratigraphic break occurring in the latter case.

5. Many stratigraphic breaks of greater or less extent develop in connection with coral reefs. The reef organisms build to the surface of the water, and upward growth then ceases, not to begin again until sea level rises with respect to the surface of the reef, but there may be more or less lateral growth. When sea level rises, the reef is again built to the surface and lateral growth repeated. Thus, extremely elusive breaks are created. The general situation is shown in the diagram of figure 27.

Unconformities in marine deposits generally have wider extent and denote longer time intervals than those in continental deposits. The latter, however, are not uncommonly the more impressive. The magnitude of an unconformity can be measured only by the duration of the lost interval, and the fossils in the enclosing rocks may afford the only clue to this duration. Neither the prominence of the unconformity nor the coarseness of the sediments which lie upon it is indicative of its importance or duration. Much

[65] Johnson, D. W., Shore processes and shoreline development, 1919, p. 256.

may be told from the metamorphism, intrusive effects, and deformation of the lower rocks as compared to those above, the differences being suggestive but not decisive of magnitude. A disconformity cannot be told from a diastem by the coarseness of the succeeding deposits. Fossils and the missing strata afford the only clues, and the former are not always reliable. It has been pointed out by Goldman[66] that unconformities are often indicated by glauconite for a foot or so above the break where it is associated with coarse clastics, and if glauconite exists elsewhere in the overlying formation, that adjacent to the break has more irregular surfaces, larger grains, and is of deeper color. Cayeux[67] much earlier suggested that there is a relation between phosphate beds and the movement of sea level, and that glauconite has similar relations. However, there is much glauconite bearing no relationship to unconformities, and the same is true of phosphate, and thus these criteria lose in value.

Every period of stability on a land must have seen many parts of the bottoms of the adjacent shallow waters brought to the position of the profile of equilibrium. Any submergence following such a period of stability led to the development of a disconformity, and such should be present in greater or less numbers in the rocks of those geologic periods which are traditionally described as having this or that continent in a base-leveled condition. Such great marine invasions as the Cambrian, Ordovician, Silurian, and Cretaceous must have led to the development of many diastems and disconformities recording times of no deposition or submarine erosion, and such should be expected and sought for.

RIPPLE MARK AND ITS INTERPRETATION

BY E. M. KINDLE[68] AND W. H. BUCHER

Beds of sand exposed either to wave action or to currents of air or water of the proper degree of intensity become covered by the flutings known as ripple marks. These may be seen on sand dunes, lake and sea beaches and bottoms, and on river beds. Parallelism of troughs and ridges characterizes the forms commonly called ripple marks, but a variety of irregularly shaped forms of water sculpture are properly included under this term.

Granular sediments with little or no cohesion between the composing particles are essential to ripple-mark formation in water. Ripple mark develops on all types of sands, but is more universal on siliceous sands because of their greater abundance. Mud, marl, and other cohesive sediments

[66] Goldman, M. I., Lithologic subsurface correlation of the "Bend Series" of North Central Texas, Prof. Paper 129, U. S. Geol. Surv., 1921, p. 4.

[67] Cayeux, L., Génèse des gisements de phosphates de chaux sédimentaires, Bull. Soc. Géol. France, vol. 5, 1905, pp. 750–753.

[68] Published with permission of the Director, Geological Survey of Canada.

are never ripple-marked by water; when dry and in the form of dust, they may be ripple-marked by wind. It sometimes happens that a deposit of mud abruptly passes into one of sand; in such case ripple mark on the sand stops abruptly at the line of contact with the mud. The limitation of ripple mark to granular sediments affords an important clue to the original texture of the materials of ripple-marked limestones.

A record of the work of air and water currents has been inscribed in terms of ripple mark on some of the oldest of the sedimentary rocks, and from a study of ripple mark much may be gleaned concerning the history of these older sediments. Fossil ripple mark should indicate whether the material impressed by it was laid down under wave or current action, by water or by wind, and, if currents were present, their directions and within certain limits their velocities. Where both fossils and ripple mark are preserved in the same beds, the correct interpretation of the latter may aid greatly in understanding the environmental conditions of the former.

It is evident that any trustworthy interpretation of the significance of fossil ripple mark must rest upon a detailed study of the conditions under which it is now being formed. Such studies have shown that all examples of ripple mark can be classified into a few types which are the product of definite geologic agents. A definite and distinctive type of ripple mark always results from water-current action on a sandy bottom, a different type from wave action, and still another type from the direct action of wind on sand or dust. If these different types can be recognized by the geologist as examples of fossil ripple mark, their discrimination will in many cases afford important aid in determining the history of the formations with which he has to deal.

In the study of ripple mark, both the experimental and observational methods have contributed in an important way to knowledge of the subject. Among those who by noteworthy experimental studies have contributed to the development of the physical theory of ripple mark are Hunt,[69] De Candolle,[70] Darwin,[71] Forel,[72] and Gilbert.[73] A host of contributions from

[69] Hunt, A. R., On the formation of ripple mark, Proc. Roy. Soc. London, vol. 34, 1882, pp. 1–19.

[70] De Candolle, C., Rides formées à la surface du sable déposé au fond de l'eau, Arch. Sci. Phys. Nat., Genève, vol. 9, 1883, pp. 241–278.

[71] Darwin, G. H., On the formation of ripple mark in sand, Proc. Roy. Soc. London, vol. 36, 1883, pp. 18–43.

[72] Forel, F. A., La formation des rides du Leman, Bull. Soc. Vaudoise Sci. Naturelles, vol. 10, 1870, p. 518; Les rides de fond dans le golfe de Morgues, op. cit., vol. 15, 1878, pp. 66–68, 76–77; Les rides de fond étudiées dans le Lac Leman, Arch. Sci. Phys. Nat., Genève, vol. 10, 1883, pp. 39–72.

[73] Gilbert, G. K., Ripple-marks, Bull. Philos. Soc. Washington, vol. 2, 1880, pp. 61–62; Ripple-marks, Science, vol. 3, 1884, pp. 375–376; Ripple-marks and cross-bedding, Bull. Geol. Soc. Am., vol. 10, 1899, pp. 135–140; The transportation of debris by running water, Prof. Paper 86, U. S. Geol. Surv., 1914.

the descriptive or observational point of view which range in importance from brief notes to elaborately illustrated papers have been made by other geologists. Only a few of these can be mentioned in the following historical sketch of the growth of knowledge concerning ripple mark.

Nomenclature

The phenomenon generally known as ripple mark has been described under various names, as ripple-drift, current-drift, current-mark, wave mark, and friction mark. The first three terms have been pretty generally discarded. Wave mark is now generally applied to the faint thread of sand, or swash mark, marking the upper limit of a wave on a beach. Gilbert used the terms "dune" and "anti-dune" for migrating ripple ridges, but the pre-emption of the word dune for large eolian hills of sand makes its use for ripple mark confusing. For the larger forms allied to ordinary ripple marks, sand waves, tidal sand ridges, and the recently coined names meta-ripples and para-ripples are among the terms which have been used. Bucher[74] has defined the term "sedimentary ripples" so as to include all of these forms as well as beach cusps and longitudinal dunes. These last two structures are not, however, included in the term ripple mark as here used.

Comparison and description of different types of ripple mark involve the use of certain terms which are defined as follows.

The *amplitude*[75] is the elevation of the ripple ridge above the trough.

The *wave length* is the distance from crest to crest of the ripple ridges.

The *ripple index* is the wave length divided by the amplitude.

Historical Sketch[76]

The data which are indispensable for an adequate interpretation of any given part of the geologic record naturally fall into three groups: (1) an accurate and exhaustive knowledge (description) of the forms constituting this record, their vertical range (in the stratigraphic sense) and areal distribution; (b) a quantitative knowledge of all factors which determine these forms and their horizontal distribution and vertical range in nature; (c) a

[74] Bucher, W. H., On ripples and related sedimentary surface forms and their paleogeographic interpretation, Am. Jour. Sci., vol. 47, 1919, pp. 207–208.

[75] In Kindle's paper (Recent and fossil ripple-mark, Mus. Bull. 25, Geol. Surv. Canada, 1917) amplitude is used to signify the distance from crest to crest. This use is in conformity with a common dictionary definition in which width or breadth is indicated as the primary meaning of the word. In one of his papers (The descriptive nomenclature of ripple-mark, Geol. Mag., vol. 41, 1904, pp. 410–418) Hunt has pointed out the objections to the use of amplitude in the sense of height.

[76] This is entirely the work of Professor Bucher.

quantitative knowledge of all factors which determine the preservation of these forms.

The following historical sketch will trace briefly the growth of information in each of these groups.

FORM, RANGE, AND DISTRIBUTION. In his "Geological Observer" Sir Henry De la Beche gave a classical account of modern and fossil ripples, clearly describing two fundamental types, the symmetrical (oscillation) and the asymmetrical (current) ripples.[77]

The difference between the sharp-crested positive and rounded form of the negative (mold) of the symmetrical ripples, although emphasized repeatedly in the following decades,[78] has only recently been recognized by geologists.[79]

De la Beche devoted a separate, though primitive, illustration to the "unequally distributed and variable formed elevations and depressions," recently called linguoid ripples by Bucher, which are common in fluvial and shallow-water sediments, but have only much later been described satisfactorily in geologic literature (Fuchs,[80] Cox and Dake,[81] Kindle,[82] and Bucher[83]). Their form was analyzed by Blasius.[84]

Similarly, the polygonal, cell-like pattern of interference ripples, described by Hitchcock[85] as "tadpole nests," although occasionally referred to and figured, has not generally been recognized as a necessary constituent of rippled sediments. Many negatives of these interference ripples in geological collections are still labelled "curiosa" or are classed with bodies of concretionary origin.

The valuable differences between current ripples of aquatic and eolian

[77] The geological observer, 1851, pp. 87, 113, and especially 506–509. The first edition which appeared in 1835 under the title "How to observe" is not accessible to the writer.

[78] Jukes, J. B., Manual of geology, 3rd ed., 1872, pp. 162–164; Fuchs, T., Studien über Fucoiden und Hieroglyphen, Denks. Akad. Wiss., Wien, vol. 62, 1895, p. 372, figs. 1–2; Van Hise, C. R., Principles of North American Pre-Cambrian geology, 16th Ann. Rept. U. S. Geol. Surv., pt. i, 1896, pp. 719–721.

[79] Very few textbooks refer to this difference. Some of the best use the negative to illustrate "ripple marks," as, e. g., Dana, J. D., Manual of geology, 1895, p. 95; Chamberlin and Salisbury, Geology, vol. 1, 1906, p. 371.

[80] Fuchs, T., op. cit.

[81] Cox, G. H., and Dake, C. L., Geologic criteria for determining the structural position of sedimentary beds, Bull. School of Mines, Univ. Missouri, vol. 2, 1916.

[82] Kindle, E. M., op. cit., 1917.

[83] Bucher, W. H., op. cit., 1919.

[84] Blasius, H., Über die Abhängigkeit der Formen der Riffeln und Geschiebebänke vom Gefälle, Zeits. f. Bauwesen, vol. 60, 1910, pp. 466–472.

[85] Hitchcock, E., Ichnology of Massachusetts, 1858, pp. 168–169; Kindle, E. M., An inquiry into the origin of *Batrachioides* the *antiquor* of the Lockport dolomite of New York, Geol. Mag., vol. 1, 1914, pp. 158–161.

origin, in the ratio of wave length to amplitude, was first observed by Cornish[86] and later independently by Kindle.[87]

Large ripples, the para-ripples of Bucher, with wave lengths measured by feet rather than inches, were described as early as 1838 from the Upper Ordovician of the Cincinnati Anticline.[88] Owing to their abundance in the Eden and Richmond divisions, they have frequently been referred to and described in publications on the local geology of Kentucky, Ohio, and Indiana. More recently, isolated occurrences have been described from the Silurian, Devonian, and Mississippian of eastern and central United States and from the Comanchean of Texas.

Ripples of similar dimensions, but generally of much more pronounced asymmetry, the meta-ripples of Bucher, abound on sand bars exposed after a flood and on tide-swept flats. They were repeatedly described and in one instance mapped in minute detail by engineers of the Mississippi River Survey.[89] The tidal meta-ripples, while mentioned in earlier writings on ripples, were not described adequately until 1901.[90]

Beautiful illustrations of modern and fossil ripples were given in the comprehensive paper published by Kindle in 1917, together with a wealth of observations. This paper represents the results of the first systematic extensive and intensive field studies made by a geologist since the days of Lyell and De la Beche.

Most formal observations on ripples have been made more or less casually without reference to their areal distribution. The greatest depth to which oscillation ripples actually can form early attracted attention. As early as 1841, the French engineer, Siau,[91] published an account of white ripples of coral sand separated by troughs filled with black grains of basalt which he observed at St. Gilles, near the westernmost point of the Island of Bourbon (Réunion) in the Indian Ocean, and by an ingenious method traced down to a depth of 188 m. (617 feet).

[86] Cornish, V., On snow waves and snow drifts in Canada, Geog. Jour., vol. 20, 1902' p. 105; On desert dunes bordering the Nile delta, Ibid., vol. 15, 1900, pp. 27–28.

[87] Kindle, E. M., Recent and fossil ripple mark, Mus. Bull. 25, Geol. Surv. Canada, 1917, p. 12.

[88] Locke, J., Geological Report, Geol. Surv. Ohio, 2nd Ann. Rept., 1838, p. 247, pl. 6.

[89] Suter, C. R., Rept. Chief Eng., U. S. A., vol. 2, 1875, p. 502; Johnston, J. B., Result of sand wave and sediment observations, Ibid., 1879, pp. 1963–1967; Ockerson, J. A., On a minute survey of a sandbar in Mississippi River, Ibid., 1884, p. 2571; Hider, A., Mississippi River Commission Rept., 1882, pp. 83–88.

[90] Cornish, V., Sand waves in tidal currents, Geog. Jour., vol. 18, 1901, pp. 170–202; On tidal sand ripples above low water mark, Rept. Brit. Assoc., 1900, pp. 733–734; On the formation of wave surfaces in sand, Scottish Geog. Mag., vol. 17, 1901, pp. 1–11; Waves of sand and snow, 1914, p. 278.

[91] Siau, M., Observations diverses faites en 1839 et 1840, pendant un voyage à l'Ile Bourbon, Compt. Rend., Acad. Sci. Paris, vol. 12, 1841, pp. 774–775; Action des vagues à de grandes profondeurs, Ann. Chim. et Phys., vol. 2, 1841, pp. 118 ff

In most similar observations at much lesser depths, little attempt has been made to describe the ripples with reference to the total configuration of the coast and the adjoining parts of the water body, that is, to understand them as an integral part of a definite dynamic and topographic system. As two notable exceptions we may quote Forel's classical investigations on Lake Geneva[92] and Cornish's studies on tidal meta-ripples.[93]

Forel showed that the depths to which oscillation ripples may form is limited by the size of the waves which, in turn, depends primarily on the size of the water body. He also noted that at any given locality the position of the ripples remains unchanged and corresponds to the orientation of the strongest waves on the lake surface which, in turn, depends primarily on the line of greatest fetch of the wind.

In the case of asymmetrical meta-ripples formed by the strong tidal currents of the British coast, Cornish showed that on the open sea-shore, as well as in the estuaries, they trend essentially at right angles to the shoreline.

Only two systematic areal studies of fossil ripples are known to the writer: one on the oscillation ripples of the Bedford and Berea formations of Ohio by Hyde[94] and the other on the large para-ripples of the Eden and Richmond series and the Brassfield formation of central Kentucky by Bucher.[95]

A later analysis of Hyde's observations by Bucher suggests that the remarkable uniform trend of the Bedford-Berea ripples is due to the action of monsoons. The para-ripples of the Ordovician and Silurian of Kentucky (and ad'oining states), on the other hand, are considered as the product of tidal currents, more or less reinforced by wind drift.

Quantitative Studies of Factors Determining Form and Distribution. The problem of the qualitative and quantitative character of the factors which determine the origin and form of ripples forced itself independently upon workers in widely separated fields of research outside the confines of geology, and their experiments and observations have furnished most of the data upon which our present understanding of the process of ripple formation is based.

The qualitative nature of the process was, however, already correctly recognized by such master observers as Lyell and De la Beche, who had no doubt that the "furrows and ridges" were "produced by the fric-

[92] Forel, F. A., op. cit., 1878, p. 66; op. cit., 1883; Le Leman, Lausanne, vol. 2, 1895, pp. 248 ff.

[93] Cornish, V., Sand waves in tidal currents, Geog. Jour., vol. 18, 1901, pp. 170–202.

[94] Hyde, J. E., The ripples of the Bedford and Berea formations of central Ohio, etc., Jour. Geol., vol. 19, 1911, pp. 257–269.

[95] Bucher, W. H., Large current-ripples as indicators of paleogeography, Proc. Nat. Acad., Sci., vol. 3, 1917, pp. 285–291; On ripples and related sedimentary forms and their paleogeographic interpretation, Am. Jour. Sci., vol. 47, 1919, pp. 149–210, 241–269.

tion . . . of currents over arenaceous accumulations"[96] and that "they are formed equally by currents of wind . . . and under water."[97] De la Beche also knew that oscillation ripples could be readily reproduced artificially in "sand . . . acted upon by agitating water above it in conveniently formed vessels of sufficient dimensions."[98]

In 1882 Hunt[99] published the results of his systematic experiments "On the formation of ripple mark," and a few months later De Candolle set forth the results of experiments in which he had studied from a broad point of view the rippling of the contact surfaces existing between a "viscous" substance, that is, one consisting of mobile particles with considerable friction (like viscous liquids, dust, sand), and a liquid of low viscosity, moving past each other.[100] In November of the same year G. H. Darwin[101] published his classical observations on artificial ripples in sand, and finally in the same year Forel[102] summarized his exquisite experimental and field observations on oscillation ripples.

Through this important group of papers, dealing almost exclusively with oscillation ripples, the laws determining their formation and existence were definitely established. The more important of these laws are as follows: Oscillation ripples owe their origin to an oscillatory movement of the water; they are stationary; their wave length grows with the velocity of the oscillatory movement and with the size of the sand grains; they can form and exist only within rather narrow limits of velocity; once formed they are unaffected by weaker oscillatory movements of the water.[103]

However, these papers placed undue importance upon oscillation ripples and upon waves as a cause of ripples. Hunt wrote "to prove that ripple-marks formed under water are, as a rule, completely independent of the rise and fall of tides, of tidal currents, of sea beaches; and that they have little in common with the current mark that owes its origin either to a continuous current of air or of water." De Candolle considered an "oscillatory" or "intermittent" movement of the water as indispensable to the formation of ripples, meaning by "intermittent" a current constant in direction but variable in velocity. Indirectly, at least, this assumption found the support of Darwin, who wrote: "I feel some doubt as to the view

[96] De la Beche, H. T., The geological observer, 1851, pp. 87, 113, 506–509.

[97] Lyell, C., Principles of geology, 11th ed., 1872, p. 342.

[98] De la Beche, H. T., op. cit., p. 508.

[99] Hunt, A. R., On the formation of ripple mark, Proc. Roy. Soc. London, vol. 34, 1882, pp. 1–8 ff.

[100] De Candolle, C., Rides formées à la surface du sable déposé au fond de l'eau, Arch. Sci. Phy. Nat., Genève, vol. 9, 1883, pp. 241–278.

[101] Darwin, G. H., op. cit., 1883.

[102] Forel, F. A., op. cit., 1878, p. 66; op. cit., 1883; op. cit., 1895.

[103] For a systematic discussion and additional facts see Bucher, op. cit., 1919, p. 192.

that a regular series of dunes may be formed by uniform current; at any rate, in my experiments the dunes were irregular and had no definite wave length." Current ripple mark thus assumed secondary importance, and its origin appeared to be linked with a mysterious factor responsible for the "intermittent" character or "pulsations" of the currents.

These pulsations still figure in Baschin's excellent paper[104] in which he viewed the sedimentary ripples as specific cases of the general law which treats the wave form as the necessary surface of equilibrium between two liquids moving at different velocities, or between a liquid and a sediment. The true value of this conception of current ripples as the necessary form of surface of contact separating the moving water and the sediment was not realized until, at the beginning of this century, systematic experiments on the transportation of sediment by running water were begun on a large scale.[105]

Quantitative experimental determinations of the factors involved in the formation and existence of current ripples were published by Hahmann.[106] His results show that, excepting the difference in form and behavior (traveling) which follow from the contrast between oscillatory and continuous current, the laws govering the formation of current ripples are identical with those of oscillation ripples. There can be no doubt that both are the result of the same process and that oscillation ripples are but a modification of current ripples, resulting from the rhythmic reversal of the current.

In the course of the hydraulic experiments to which reference has been made, the less common forms of rhomboid and linguoid ripples attracted attention and were studied in detail, the former by Engels, the latter by Blasius.

Reynolds[107] had observed the formation of current ripples while experimenting with artificial tidal currents in his model estuary. Without entering into an analysis of the physics of these ripples, he assumed from the ratio of this model to nature that real tidal currents should give rise to truly gi-

[104] Baschin, O., Die Entstehung wellenähnlicher Oberflächenformen, Zeits. Gesell. Erdkunde, vol. 34, 1899, pp. 408–421.

[105] Eger, Dix, and Seifert, Versuch über die Bettausbildung der Weserstrecke von Km. 303–306, Zeits. f. Bauwesen, vol. 56, 1904, pp. 323–344; Engels, H., Untersuchungen über die Bettausbildung gerader oder gekruemmter Fluss-strecken mit beweglicher Sohle, Ibid., vol. 55, 1905, pp. 663 ff.; Blasius, H., Über die Abhängigkeit der Formen der Riffeln und Geschiebebänke vom Gefälle, Ibid., vol. 60, 1910, pp. 466–472; Gilbert, G. K., The transportation of debris by running water, Prof. Paper 86, U. S. Geol. Surv., 1914.

[106] Hahmann, P., Die Bildung von Sanddünen bei gleichmässiger Strömung, Ann. Phys., 1912, pp. 637–676. See also Bucher, op. cit., 1919, pp. 153–164.

[107] Reynolds, O., Reports of the Committee on the action of waves and currents, Rept. Brit. Assoc., 1887, pp. 555–562; 1889, pp. 328–343; 1890, pp. 512–534; 1891, pp. 386–404.

gantic ripples with a wave length of 80 to 100 feet. The same arbitrary hypothetical enlargement of scale has led to the assumption that the large subaerial dunes, which in regions of constant wind direction reach a remarkable degree of regularity in wave length and height, are merely full-grown eolian current ripples.[108]

In all hydraulic experiments it soon became evident that above a certain critical velocity current ripples in water cease to exist. Gilbert's[109] observations have clearly brought out the fundamental change in the relation of the overlying fluid to the sediment which sets in when the ripples disappear. In his experiments with still higher velocities, the wave form reappeared, but was under radically different dynamic conditions, as direct friction waves without the intercalation of vertical vortices. The probable relation between these unstable "sand waves," which disappear when the velocity drops below the critical value, and the larger forms of ripples (meta- and para-ripples) was discussed by Bucher.[110]

Since a similar critical velocity in air currents destroys eolian current ripples after they have reached a maximum size measured in centimeters, the existence of regular current ripples of one to several meters' wave length and of regular dunes of similar height and a uniform wave length of several kilometers[111] presents a difficult problem. Its solution seems to be contained in the observations of King,[112] which definitely established the tendency of air currents to assume the form of stationary waves in the lee of an obstacle. This leads to the assumption that for every obstacle of given size and wind of a given average velocity "there exists a sinuous surface which, when established, offers a minimum of friction. Whether the surrounding surface be flat or consists itself of independent dunes, all fortuitous changes in the distribution of the sand must gradually lead toward the formation of this optimum surface,"[113] provided velocity and direction of the wind remain unchanged for a sufficient length of time.

For the purpose of the geologist, the knowledge of the physical factors determining the form and dimensions of ripples is of value only when translated into terms of geographical conditions. This translation has been left almost entirely to the geologist, who only in the last two decades has thoroughly realized the complexity of the task.

[108] Cornish, V., Progressive waves in rivers, Geog. Jour., vol. 29, 1907, pp. 23–31.

[109] Gilbert, G. K., op. cit., 1914.

[110] Bucher, W. H., op. cit., 1919, pp. 165–182.

[111] Hedin, S., Scientific results of a journey in Central Asia, see volumes 1 and 2 for ripple mark, dune formation, etc., 1899–1902.

[112] King, W. J. H., The nature and formation of sand ripples and dunes, Geog. Jour., vol. 47, 1916, p. 189–209. It is interesting to note that Forel in his experiments on oscillation ripples observed that the presence of a linear obstacle of small height greatly facilitated the formation of ripples.

[113] Bucher, W. H., op. cit., 1919, pp. 147–199, 201–202.

Two examples may serve to illustrate the uncertainty and errors that attach to most earlier reasoning about ripples.

Zimmermann[114] described small ripples from one of the layers of salt separated by very thin laminæ of anhydrite which were found in a drill core from the Zechstein at Schlitz in Hesse. Since this salt is part of the vast Permian deposits generally known as the Stassfurt salts, any definite information concerning the depth of the water body at any given locality would be of considerable interest. Zimmermann concluded that these ripples could have formed only under a very thin cover of water, perhaps but a few decimeters in depth, "else no ripples or at least none of such small size could have formed." Yet Siau had found ripples of similar dimension at a depth of 617 feet in the Indian Ocean.

The other extreme is represented by Gilbert,[115] who thought he had found oscillation ripples, 6 inches to 3 feet in height and 10 to 30 feet from crest to crest, in the Medina sandstone. He arrrived at the conclusion that these large ripples must have been produced through the action of waves no less than 60 feet high. The only point overlooked in this argument of far-reaching paleogeographical consequences vitiates its conclusions, namely, the existence of a critical current velocity, above which neither current nor oscillation ripples can form or exist.

The three comprehensive papers which have appeared since 1916[116] mark rapid strides forward toward an adequate understanding of the factors involved in the formation of the various forms of ripples.

Preservation of Ripple Mark

The question why one or the other type of ripples is not found in a certain sediment leads to this alternative: either they were not formed or were not preserved. For an adequate interpretation of the fossil sedimentary record, therefore, the factors which favor or prevent preservation are as important as those involved in the formation of ripples. They have barely been referred to, or not at all, in most of the earlier literature on ripple mark. The first attempt at a systematic discussion is contained in Bucher's paper of 1919.

[114] Zimmermann, E., Steinsaltz mit Wellenfurchen, etc. [Schlitz in Hessen], Zeits. d. Deut. geol. Gesell., vol. 60, Monatsb., 1908, p. 70.

[115] Gilbert, G. K., Ripple-marks and cross-bedding, Bull. Geol. Soc. Am., vol. 10, 1899, pp. 135–140; H. L. Fairchild showed that these are not ripples, see Beach structure in Medina sandstone, Am. Geol., vol. 28, 1901, pp. 9–14.

[116] Johnson, D. W., Contributions to the study of ripple-marks, Jour. Geol., vol. 24, 1916, pp. 809–819; Kindle, E. M., Recent and fossil ripple-mark, Mus. Bull. 25, Geol. Surv. Canada, 1917; Bucher, W. H., On ripples and related sedimentary forms and their paleogeographic interpretation, Am. Jour. Sci., vol. 47, 1919, pp. 149–210, 241–269.

Wind Ripple Mark

The ease with which every feature connected with the development of wind-made ripple mark can be observed makes it convenient to begin the study with the examination of eolian ripple mark. This finds its best development on the surfaces of sand dunes, but frequently may be seen on lake and sand beaches. Wind ripples also form in dusts and other fine materials.

Wind ripple mark is asymmetrical, the windward slope of slight inclination, the leeward steep.[117] The wave length and amplitude seem to vary little with wind velocity,[118] but they do vary somewhat with the size of the

FIG. 78. WIND RIPPLE MARK

The wind blew from left to right. Photograph by Doctor E. M. Kindle at a place west of Port Colborne, Ontario.

particles,[119] the largest wave lengths and the greater amplitudes being attained in the coarser sands. Both components vary within narrow limits, the majority of the former falling between 2 and 4 inches and the latter between 1/8 and 1/4 inch (fig. 78). Kindle records the occurrence of irregular ripples in coarse sands on the shores of Lake Erie with wave lengths up to 10 inches. The ripple index is relatively large.

[117] Lyell, C., The student's elements of geology, 6th ed., 1841, pp. 41–43. Lyell's description of the formation of wind ripple mark can hardly be improved upon.

[118] Kindle, E. M., op. cit., 1917, p. 10.

[119] Sokolow, N. A., Die Dünen, Bildung, Entwicklung und innerer Bau, German translation by Arzruni, A., 1894, p. 15.

Wine ripples approach parallelism, but commonly are not straight. They anastomose in broad net-like patterns and do not appear to have such extensive continuity as does water ripple mark.

The crests of wind ripple marks should contain coarser particles than occur in the troughs and on the slopes, but the distinction in many cases is difficult to make.

Figure 79a, which illustrates diagrammatically the mode of formation of wind ripple, will also show by comparison with figure 79b the essential difference between wind and water-current ripple mark. The height of the crest of the latter is always greater than the former when the wave lengths are approximately the same.

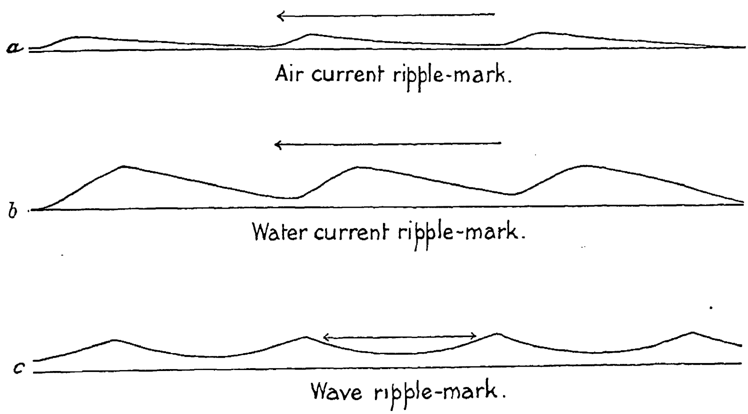


FIG. 79. DIAGRAMMATIC ILLUSTRATIONS OF TYPES OF RIPPLE MARK
Drawn by Doctor E. M. Kindle

WIND RIPPLE MARK ON SNOW. In cold climates wind ripple mark is sometimes formed on dry and granular snow. The cohesion of snow flakes or particles varies with the temperature and consequent moisture, so that ripple mark forms on snow only at temperatures considerably below the freezing point. With low temperature and the right type of powdery snow, a winter gale almost always develops over parts of a large level expanse of snow a type of asymmetric ripple with a highly variable wave length, which differs conspicuously from eolian sand ripple mark in having its steep face on the windward instead of the leeward side. Symmetrical ripple mark with a wave length of several inches sometimes forms on snow, but it is a relatively rare phenomenon. Obviously the shape of the ripples as reported in these observations is due to peculiar conditions inherent in the properties of snow which have not been analyzed so far.

Ripple Mark Formed by Water Currents

CRITICAL CURRENT VELOCITY. The surface of sand when exposed to a current of water is set in motion when the current reaches a velocity sufficient to drag some of the surface particles along with it, and at certain velocities ripple mark forms in the moving surface layer. Its development results through the operation of the general principle that a sinuous surface of contact between a moving fluid and a sediment offers a minimum of friction for certain velocities.

Below a certain velocity, a current is unable to move the débris forming its bed. The point at which, with increasing velocity, motion is started, is called the "first critical point" in the following discussion.[120]

The velocity represented by the first as well as the second and third critical points to be mentioned later differs according to the grade or coarse-

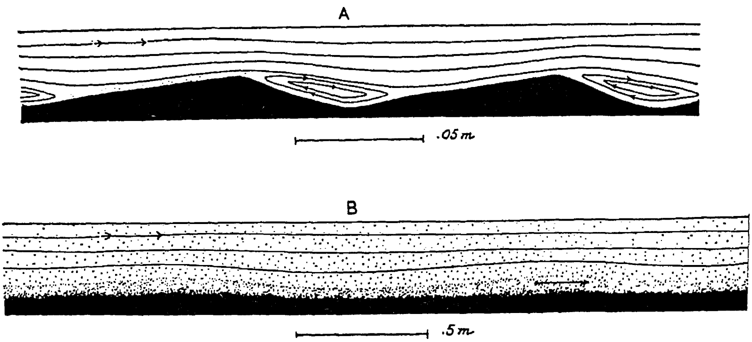


FIG. 80. DIAGRAMS CONTRASTING THE MOVEMENT OF SAND GRAINS AND CURRENT IN CURRENT RIPPLES (*A*) AND SAND WAVES (*B*)

Drawn by Doctor E. M. Kindle

ness of the débris. In each case, however, the critical point of current velocity is the velocity which is correlated with a radical change in the behavior of the sediments which are subjected to it.

The results of three series of determinations of the first critical point by Umpfenbach, Login, and Gilbert have been brought together by Bucher[121] and are given in table 89.

CURRENT RIPPLES. Shortly after the first critical point of the current is reached, current ripples develop consisting of numerous essentially parallel, long, narrow, more or less equidistant ridges trending at right angles to the

[120] It corresponds to the lower critical velocity of Lechalas and to the velocity competent for traction of Gilbert's nomenclature, Gilbert, op. cit., 1914, p. 194.

[121] Bucher, W. H., op. cit., 1919, p. 151.

current. These ridges are asymmetrical in profile, with a steep lee-side and a gentle stoss-side slope (figs. 81–83).

The lines of flow, as represented in figure 80, were first recognized and figured by Darwin,[122] who demonstrated the existence of a vortex on the lee-

TABLE 89

APPROXIMATE CURRENT VELOCITIES NECESSARY TO MOVE DÉBRIS OF DIFFERENT SIZES*

DESCRIPTION	MEAN DIAMETER	DEPTH	VELOCITY
	mm.	*m.*	*m./sec.*
Brick clay, allowed to settle from suspension (L)		(Shallow)	0.08 (s)
Fine loam and mud (U)		(Shallow)	0.32 (s)
(Fine sand) (G)	0.4	0.13	0.26 (m)
(Sand) (G)	0.5	0.12	0.28 (m)
Fresh-water sand (L)		(Shallow)	0.20 (s)*
(Sand) (G)	0.7	0.2	0.34 (m)
Sea sand (L)		(Shallow)	0.34 (s)
Coarse sand (L)		(Shallow)	0.49 (s)
(Coarse sand) (G)	1.7	0.006	0.34 (m)
(Fine gravel) (G)	3.2	0.028	0.46 (m)
Rounded pebbles size of peas (L)		(Shallow)	0.61 (s)
Very small pebbles (U)		(Shallow)	0.65 (s)
(Fine gravel) (G)	4.9	0.033	0.65 (m)
(Fine gravel) (G)	7.0	0.066	0.86 (m)
Gravel (U)	27.0	(Shallow)	0.97 (s)
Gravel (U)	54.0	(Shallow)	1.62 (s)
Boulders (U)	171.0	(Shallow)	2.27 (s)
Boulders (U)	323.0	(Shallow)	3.25 (s)
Boulders (U)	409.0	(Shallow)	4.87 (s)
Boulders (U)	700–800	(Shallow)	11.69 (s)

* (U) = Umpfenbach, quoted from Penck, Morphologie der Erdoberfläche, vol. 1, 1894, p. 283.

(L) = Login, Proc. Roy. Soc. Edinburgh, vol. 3, 1857, p. 475.

(G) = Gilbert, G. K., Prof. Paper 86, U. S. Geol. Surv., the first three figures from table 9, p. 69, and the others from the averages on p. 71.

Also: (s) equals surface velocity and (m) mean velocity.

Login's and Gilbert's figures have been transformed from inches to the nearest millimeter and from feet to the nearest centimeter.

side by placing a drop of ink in the trough between two ripples. The action of this vortex causes small particles to creep upstream on the lee-side of a ripple.[123]

[122] Darwin, G. H., On the formation of ripple-mark in sand, Proc. Roy. Soc. London, vol. 36, 1883, pp. 18–43.

[123] Bertololy, E., Kräuselungsmarken und Dünen, Münchener Geog. Studien, 9. Stueck, 1900, p. 86.

FIG. 81. WATER-CURRENT RIPPLE MARK

These current ripple marks were made on sands of Nantasket Beach, Massachusetts. The currents which formed the ripples were quite regular and moved from right to left. It will be noted that the steeper slopes are on the side opposite to that from which the currents came. After Johnson, D. W., Shore processes and shoreline development, 1919, p. 495.

FIG. 82. WATER-CURRENT RIPPLE MARK WITH MOLLUSK AND WORM TRAILS

The current moved from left to right. Photograph by Doctor E. M. Kindle.

Current ripples travel downstream as the grains are rolled up the gentle slope and dropped into the vortex of the lee-side to be deposited there.[124] It should be noted that the ripple as such is absolutely rigid, while just the grains of the top layer roll along the surface, no grains being carried in suspension.

The gentler slopes of current ripple mark are invariably up-current. In shallow streams with relatively smooth bottoms, the ridges are essentially parallel and may extend with even and regular crests from bank to bank, some occasionally dying out, others uniting and new ones appearing. Irregularities on the bottom and bends in the stream produce irregularities in

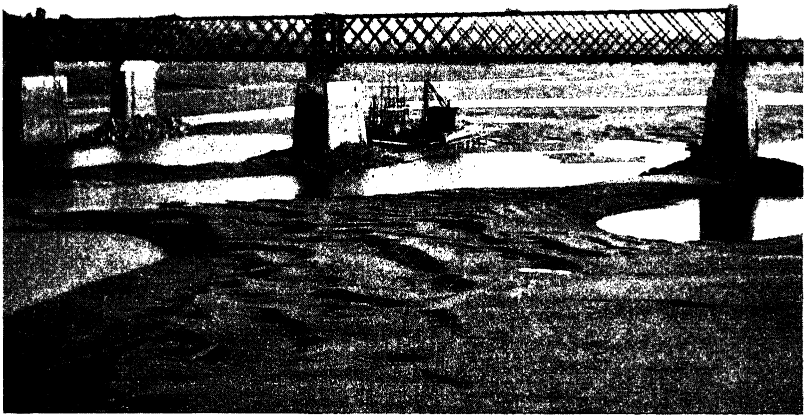


FIG. 83. LARGE WATER-CURRENT RIPPLE MARKS WITH CRESTS 10 TO 15 FEET APART
Below bridge over the Avon River, Windsor, Nova Scotia. Very much smaller current ripple marks are superimposed upon the larger. Photograph by Doctor E. M. Kindle.

wave length, amplitude, and direction. Most streams have local upstream currents, and such may develop ripple mark with reversed slopes. In bays and similar bodies of water the trends exhibit great variation, and the gentle slopes may be either seaward or landward.

As lamination is always developed on the lee-side of current ripple mark, it follows that in cases of parallel crests the cross-lamination is regular in direction of inclination, and that diversity of ripple-mark development leads to equal diversity in direction and inclination of cross-lamination.

The distribution of particles in current ripples is such that the coarsest are found in the troughs and the finest on the crests. This often is very

[124] Forel calls the stoss side, "face d'érosion," the lee-side, "face d'alluvion."

distinctly shown, and in cases of rapid deposition of sediments, successive crests and troughs may coincide o as to produce apparent cross-lamination in an up-current direction.[125]

Regressive Sand Waves. With increasing current, a second critical point of current velocity is reached when current ripples disappear and the sand surface becomes a smooth sheet of sand.[126] This is due to the fact that the mechanical effect of the current is extended below the surface, destroying the immobility of the sand bed, which is the prerequisite of the existence of current ripples. Instead of the topmost grains rolling and skipping over a bed of sand, we find a whole layer of mixed sand and water in motion, grading insensibly into the motionless substratum. Above this layer of moving sand and water we find water with little sand in suspension, the transition being not gradual but abrupt.

After the "smooth phase" following the second critical point, a third critical point was reached in Gilbert's experiments at which the sand again assumed a waved surface. At this velocity, however, the waves of sand which Gilbert called "anti-dunes" traveled upstream. For Gilbert's term Bucher has substituted that of "regressive sand waves."[127] "This movement is accomplished by erosion on the downstream face and deposition on the upstream face."[128] Cornish found this reversed motion of the ripple mark occurring when the velocity attained about 2.2 feet per second.[129] Gilbert found the development of this phase to be connected with increase of load as well as with increased velocity.

The regressive sand waves differ in shape as well as in the direction of movement from current ripples. They have symmetrical profiles and gently rounded crests.

Progressive Sand Waves. In waters carrying large quantities of sediments of high velocity above the third critical point, ripples of gigantic proportions called sand waves are developed. Hider[130] describes them as "a series of ridges irregular in shape, transverse to the direction of the current, which in deeper water and the most rapid current under favorable conditions become more regular in shape and size approaching the form of waves." Gently rounded broad crests, often nearly symmetrical, characterize these sand waves. Observations made by McMath from a diving bell in the

[125] Spurr, J. E., False bedding in stratified drift deposits, Am. Geol., vol. 13, 1894, pp. 43–47, 201–206.

[126] Gilbert, G. K., op. cit., 1914, p. 32.

[127] Bucher, W. H., op. cit., 1919, p. 165.

[128] Gilbert, G. K., op. cit., 1914, p. 11.

[129] Cornish, V., Waves of sand and snow, 1914, p. 278.

[130] Hider, A., Mississippi River Commission Rept., 1882, pp. 83–88; Chief. Eng., U. S. A., Rept., 1883, p. 2199.

Mississippi River showed a flowing motion at a depth of 2 feet below the surface of the sand wave, the velocity diminishing downward.[131]

These sand waves travel downstream like current ripple. Their broad rounded crests, however, are in sharp contrast with the angular crests and steep lee slopes of current ripple. Hider's observations appear to indicate that reduction of velocity results in the transformation of these sand waves into the large ripples seen in tidal flats and the sand bars of many rivers and creeks, and the observations of Reynolds[132] seem to support this view. Bucher explains the transformation as follows:

> As the velocity drops below the third critical point, the bodies of the waves settle and become rigid, a vortex forms on the lee side and now the weak current, like a wind on a dune, moves but the grains of the surface layer, rolling them up the weather slope and dropping them on the lee side. Since the angle of rest of ordinary materials differs greatly from the gentle slope of the sand-wave, this must undergo a fundamental change in form, from more or less symmetrical waves to strongly asymmetrical dunes.[133]

META-RIPPLES. Bucher has proposed to distinguish between the sand waves and the secondary forms derived from them by using for the latter the term meta-ripples.[134] Direct observation through the turbid waters producing these structures is extremely difficult owing to the depth and large suspended load of the water at the time the transformation is assumed to occur.

Whatever the nature of the transformation may be which takes place between the phase of maximum activity in giant ripple mark formation and the emergence of the huge sand waves left by ebbing tides in estuaries and falling flood waters in rivers, the terrace-like structures of each, with steep, usually seaward-facing[135] fronts, are distinctly asymmetric and similar in essential features; but the tidal sand waves have a greater range than those of the rivers in the size of the ripples, some of the tidal sand ridges rising 7 or 8 feet above the troughs at the mouth of the Avon River,[136] while upriver meta-ripples rarely rise more than 2 or 3 feet above their troughs.

"FULLS AND LOWS" CONTRASTED WITH META-RIPPLES. Meta-ripples with the scarp face modified by tidal action might be confused with structures commonly called "fulls and lows" on the English coast but having a very

[131] Gilbert, G. K., op. cit., p. 156.

[132] Reynolds, O., Reports of the Committee on the action of waves and currents, Rept. Brit. Assoc., 1889, p. 343.

[133] Bucher, W. H., op. cit., 1919, p. 181.

[134] Bucher, W. H., op. cit., 1919, p. 181.

[135] Cornish recorded large tidal ripples facing with the flood tide at Barmouth, N. Wales, and on the Goodwin Sands; Geog. Jour., vol. 18, 1901, pp. 171, 190.

[136] Kindle, E. M., Notes on the tidal phenomena of Bay of Fundy rivers, Jour. Geol., vol. 34, 1926, p. 645.

different origin from any kind of ripple mark. On some sea coasts a series of two or more low uniformly rounded sand ridges usually many yards in width border the sea beach, trending parallel with it in the intertidal zone or below it. Three of these sand ridges uncovered at low tide and separated by a wide depression $1\frac{1}{2}$ to $4\frac{1}{2}$ feet deep lay seaward of the shore beach at Skegness, England, during the early summer of 1928. Similar underwater structures border Point Pelee, the long sand spit extending into Lake Erie from the north shore. These "fulls" appear to be produced by breakers and the resulting undertow currents during heavy storms. They probably shift their positions only in stormy periods.

PARA-RIPPLES. Para-ripples, the large ripples found in many limestones, are considered by Bucher to be the result of current action. They vary from strongly asymmetrical to completely symmetrical and are ascribed to current rather than wave action chiefly on the evidence of lack of assortment of the materials composing them. They differ from meta-ripples chiefly in the greater number of symmetrical ripples and in the smaller index of the asymmetrical forms. It may be that they represent meta-ripples modified by wave action or by tidal currents reversed so as to have lost the original asymmetry.

Wave Ripple Mark

FORMATION. Wave ripple mark is a function of wave action. The agitation of the bottom resulting from the oscillatory movement of water produced by wave action throws the granular sediment into ripple ridges which coincide in direction with the trend of the waves. Ripple mark thus produced is characterized by the perfect symmetry of the ridges, which contrast sharply with the current ripples ordinarily seen on river bars and tide flats (fig. 84). Double or triple crests are sometimes developed in wave or oscillation ripple mark,[137] and a subordinate lower crest occupies the middle of the rather wide trough in one type of wave ripple mark. These Cornish suggests may be the result of a "settling of the sand."

Gilbert has formulated the essential elements of the theory of their formation as follows:

> The ordinary ripple-mark of beaches and rock faces is produced by the to-and-fro motion of the water occasioned by the passage of wind waves. During the passage of a wave each particle of water near the surface rises, moves forward, descends and moves back describing an orbit which is approximately circular. The orbital motion is communicated downward, with gradually diminishing amplitude. Unless the water is deep the orbits below the surface are ellipses, the longer axes being horizontal, and close to the

[137] Cornish, V., Sand waves in tidal currents, Geog. Jour., vol. 18, 1901, pp. 193–194, fig. 25.

bottom the ellipses are nearly flat, so that the water merely swings forward and back. It is in this oscillating current, periodically reversed, that the sand-ripples are formed. A prominence occasions vortices alternately on its two sides, and is thereby developed in a symmetric way with equal slopes and a sharp apex. There is a strong tendency to produce a mole laterally into a ridge, the space between ridges is definitely limited by the interference of vortices and in time there results a regular pattern of parallel ridges, equally spaced. It has been found experimentally that by varying the amplitude of the water oscillation and also by varying its frequency the size of the resulting ripples can be controlled; but the precise laws of control have not been demonstrated. Evidently the frequency of the natural oscillation equals the frequence of the wind waves, and its amplitude is a function of the size of the waves and the depth of the water; so that a relation will ultimately be established between wave-size, wave-period and water-depth as condiions and ripple-size as a result.[138]

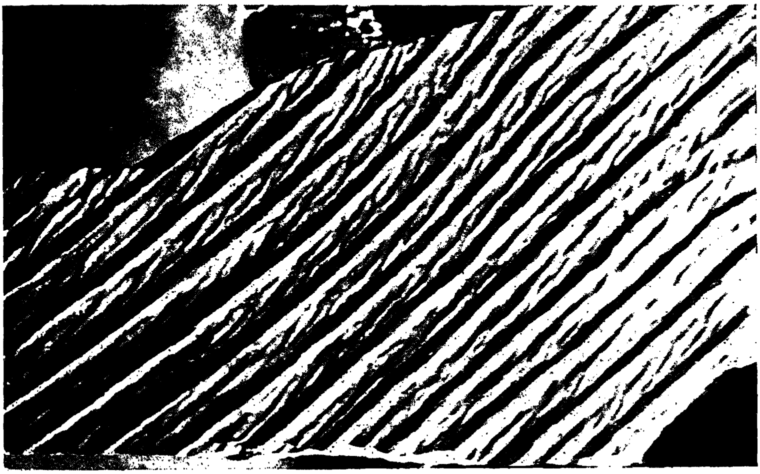


FIG. 84. WAVE RIPPLE MARK

This sandstone slab shows ripple marks which were made on an ancient sea bottom many millions of years ago. A second, somewhat later and smaller series of wave ripples began to form in the troughs of the larger ones. After G. K. Gilbert, U. S. Geol. Surv.

Darwin describes the first appearance of artificially formed oscillation ripples as follows:

When a very small quantity of sand is sprinkled in and the rocking begins, the sand dances backwards and forwards on the bottom, the grains rolling as they go. Very shortly the sand begins to aggregate into irregular little flocculent masses, the appearance being something like that of curdling milk. The position of the masses is, I believe, solely determined by the friction of the sand on the bottom, and as soon as a grain sticks, it

[138] Gilbert, G. K., Ripple-marks and cross-bedding, Bull. Geol. Soc. Am., vol. 10, 1899, pp. 137–138.

thereby increases the friction at that place. The aggregations gradually become elongated and rearrange themselves. . . . Some of the elongated patches disappear, and others fuse together and form ridges, the ridges become straighter, and finally a regular ripple mark is formed.[139]

They form equally well in oscillating currents produced in a vessel rotated alternately in opposite directions, where there is no evidence of stationary waves, or on the bottoms of water bodies agitated by waves, where the same reversal of current takes place.

OCCURRENCE. Oscillation ripples may be seen under the shallow water of most ponds and lakes. They also occur on tidal flats where the currents are not strong enough to produce current ripple.

Since ripple mark is not uncovered on the lake shore as on the seashore, its almost universal occurrence on suitable bottoms a few feet or yards from shore in water of moderate depth might never be suspected by the casual observer. Where the shoreline slopes abruptly under the water, ripple mark is not formed up to the very edge of the beach. A two-mile walk, for example, along the sandy beach of Lake Ontario near Wellington when the waves are forming ripple mark would enable one to see ripple marks along perhaps not more than 100 yards of this distance. But observations made from a small boat on this shore in water 4 to 10 feet deep would show an uninterrupted stretch of ripple-marked bottom. A water glass or a small wooden box with glass bottom will enable the observer, where the water is clear, to see the wide distribution of wave ripple mark wherever the bottom is sandy.

Oscillation ripples are stationary. They cannot advance in either direction, owing to the formation of vortices alternately on either side of the ripple as the current is reversed. Thus, the crests and troughs hold a constant position so long as the producing conditions do not increase in magnitude, in accordance with the Forel generalization[140] that "Ripples once formed do not experience a change in spacing as a result of diminishing amplitude of oscillation of the water." In the Joggins section of Nova Scotia Kindle[141] has observed symmetrical ripple mark directly superimposed throughout a 6-inch bed, and Gilbert records the occurrence of ripple mark holding the same position during the accumulation of 2 feet of sediments.[142]

The preservation of typical oscillation ripples under a thick layer of coarse

[139] Darwin, G. H., On the formation of ripple marks in sand, Proc. Roy. Soc. London, vol. 36, 1883, p. 23.

[140] Forel, F. A., Les rides de fond étudiées dans le Lac Leman, Arch. Sci. Phys. Nat., Genève, vol. 10, 1883, pp. 39–72; Transl. by Johnson, D. W., Shore processes and shoreline development, 1919, p. 512.

[141] Kindle, E. M., op. cit., 1917, p. 27.

[142] Gilbert, G. K., Bull. Philos. Soc. Washington, vol. 2, 1874–1878, pp. 61–62.

sand, as is frequently seen in many sandstone formations, offers a more difficult problem than the preservation of current ripples, as the very existence of oscillation ripples excludes the possibility of any current erosion in the vicinity of the sedimentary surface. However, the close relations sometimes observed between oscillation ripples and superposed non-rippled sandstone will be understood by geologists who are familiar with the surprisingly firm sand of certain sea beaches. At Skegness, England, for example, part of the sand beach is so firm that the sport of sailing over it in rubber-tired vehicles has developed, while adjacent to this beach are others where deep footprints are made in walking over the sand. The experienced student of ripple mark will discover in his wading observations beautifully developed oscillation ripple mark with the sand "set" so firmly that the ripples make unpleasant walking for bare feet and leave little if any trace of foot prints. Such ripple marks would survive the passage of sand-bearing currents, and speedy burial might result without damage to their form. A storm may throw a large quantity of sediment into suspension at one locality, while at another not far distant locality, its only effect on the bottom would be the production of oscillation ripples. The wind drift set up by the storm may also carry much sediment in the upper levels of the water from the former to the latter locality.

Classification of Ripple Mark

The simple forms of ripple mark are the product of either currents or waves acting alone. The successive or simultaneous action of these two agencies gives rise to complex forms. The relationships of the several kinds of ripple mark to the current and wave conditions producing them are concisely indicated in table 90.

COMPLEX FORMS OF CURRENT RIPPLE MARK. The simple types of ripple mark produced by air and water currents and waves have been described in some detail in preceding sections, and their relations are sufficiently indicated in table 90.

In this connection only those forms of ripple mark will be considered which result from combinations of simple forms or the complex operation of casual factors which in some cases do not readily admit of analysis.

LINGUOID RIPPLES. One of the modifications of the simple normal type of current ripple shows a highly irregular pattern with a wide range in the variety of forms. The tongue-like outline of the unit forms of many examples of the pattern led Bucher[143] to give it the name of linguoid. Negatives of these markings resemble small mud flows. Blasius has produced

[143] Bucher, W. H., op. cit., 1919, p. 164.

this form of ripple mark experimentally, transforming regular current mark into it.[144] For illustrations see Kindle.[145]

TABLE 90

CLASSIFICATION OF SUBAQUEOUS RIPPLE MARK

CONDITION OF WATER	TYPE OF RIPPLE MARK
I. Simple currents	
1. Current velocity between first and second critical points, with no sediment in suspension. A part of the fluid moving in horizontal vortices which are set up as grains shift on the surface of the sediment otherwise at rest.	Current ripples (asymmetrical): a. Normal b. Rhomboid c. Linguoid
2. Velocity between second and third critical points with conditions of ripple destruction.	Smooth sheet of sand
3. Velocity at third critical point and higher, with much sediment in suspension. Regressive sand waves at lower, and progressive sand waves at higher, velocities.	Sand waves (symmetrical), (exist only while current lasts) a. Regressive sand waves b. Progressive sand waves
4. Falling velocities of high range, causing transformations of the unstable sand waves.	a. Meta-ripples (asymmetrical) b. Para-ripples (symmetrical and asymmetrical)
II. Oscillating currents, due to wave action.	Oscillation ripples (symmetrical)
III. Currents of different direction, acting successively or simultaneously, causing actual or potential sets of ripples to interfere.	1. One set forming after the completion of the other a. The second set consisting of oscillation ripples. Oscillation cross ripples. b. The second set consisting of current ripples. Current cross ripples. 2. The two sets forming simultaneously. Compound ripples.

RHOMBOID RIPPLE MARK. A rare form of ripple mark called rhomboid[146] shows a reticular pattern strikingly resembling that of the scales of a ganoid

[144] Blasius, H., op. cit., 1910.
[145] Kindle, E. M., op. cit., 1917.
[146] Bucher, W. H., op. cit., 1919, p. 153.

fish. These seem first to have been noted by Williamson, who described them as resembling "the overlapping scale leaves of some cycadean stem[147]" (see p. 671).

Engels[148] found in his experiments that the first effect of transportation by a uniform current was the formation of small rhomboidal, scale-like tongues of sand. Each tongue has one acute angle pointing downstream, formed by two steep lee sides, while the other, pointing upstream, is formed by the gentle slope extending into the reëntrant angle of the lee sides of two tongues of the following alternating row. In Engels' experiments, with increasing velocity of the current, common current ripples took their place.

The rarity of this type[149] in nature is indicated by the fact that the authors have seen only two examples of it. The examples figured were found by Kindle[150] near the tip of a miniature spit on the shore of Lake Erie, assumed at the time to be the product of small cross waves. In the light of Engels' experiments, however, it seems probable that it was the product of the currents which produced the small bar. The location near the middle of a somewhat crescent-shaped bay would have favored the translation of waves entering the bay into localized currents impinging on each other at the point of the bar and forming an undertow or backwash current (fig. 85).

CURRENT CROSS RIPPLES. Cross ripples may also result from the intersection of a current with a pre-existing set of ripples, if the action of the current is sufficiently weak and of short duration. As there is no oscillation of the current, there is no reason for a transformation into the hexagonal pattern. The two sets of ripples may intersect at any angle (fig. 86).

MODIFICATION OR TRANSFORMATION OF TYPES. Ripple mark developed by current action frequently is modified by wave action. If the wind should blow at right angles to the course of a stream in which current mark is forming, or transverse to the direction of a tidal current, the ripple mark resulting from these currents will be crossed transversely by ripple mark which trends at right angles to the course of the wind. If the waves are the product of a moderate breeze and are of small size, the current ripple mark will be marked on its gentle slopes only by a miniature ripple-mark pattern which will be broken or interrupted by the troughs of the current ripples. The size or prominence of these superimposed ripples will depend on the strength of the waves producing them. Under the

[147] Williamson, W. C., On some undescribed tracks of invertebrate animals from the Yoredale rocks, and some inorganic phenomena, produced on tidal shores, simulating plant remains, Mems. Manchester Lit. and Philos. Soc., vol. 10, 1887, pp. 19–29.

[148] Engels, H., op. cit.

[149] Johnson, D. W., Shore processes and shoreline development, 1919, p. 517. Johnson suggests that this peculiar pattern is the work of a single backwash current, and he terms it backwash mark.

[150] Kindle, E. M., op. cit., 1917, pl. 19B.

influence of a strong wind they will develop to the extent of breaking across the current ripple pattern and producing a knobby surface. The ripple mark superimposed on the current mark by wave action is always of the asymmetrical type (fig. 87).

FIG. 85. PLASTER CAST OF IMBRICATED WAVE MARKINGS FORMED AT THE MARGIN OF THE BEACH BY WAVES CROSSING A MINIATURE SPIT

Beach of Lake Erie at Port Colborne, Ontario. Markings of this character are formed in the wave zone on beaches of fine sand with every retreat of waves. The watch is on the upper side of the beach. Photograph by Doctor E. M. Kindle.

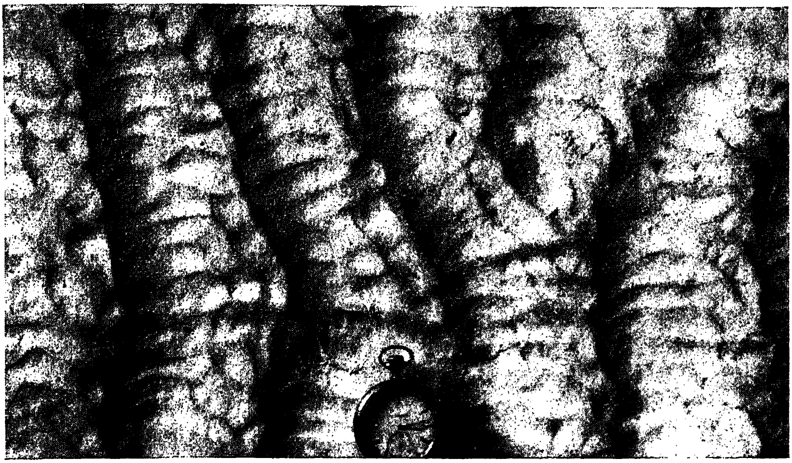


FIG. 86. TIDAL-CURRENT RIPPLE MARK WITH SUPERIMPOSED SMALL PATTERN AT RIGHT ANGLES

The latter was formed at a late stage of ebb tide when current direction was at right angles to the earlier current. Photograph by Doctor E. M. Kindle.

FIG. 87. CURRENT RIPPLE MARK MODIFIED BY WAVE ACTION

These asymmetrical or current ripple marks were made on the sands of the Avon River, Nova Scotia, just below the town of Windsor. They were later modified by waves moving oblique to the direction of the current, the finer sculpturing being the work of the waves. Photograph by Doctor E. M. Kindle.

Meta-ripples may be reshaped by waves acting in the same direction as the preceding current; their surface material is assorted and a sharp crest[151] placed in the center of the originally broad, round ridges.

Small current and oscillation ripples are in this way transformed one into the other, and nothing remains to indicate the change. Oscillation ripples are extremely sensitive even to very gentle current action.[152]

INTERFERENCE OR CROSS RIPPLES. A special form of compound rippling, to which the terms "interference ripples" or "cross ripples" should be limited, consists of polygonal, usually more or less irregular pits, arranged side by side like stones in a mosaic. Two fundamental types can be distinguished, the "rectangular" and the "hexagonal," which usually occur together and rarely show their pure form. Both consist of parallel ridges connected by crossbars. In the hexagonal type the crests of the parallel ridges zigzag, forming obtuse angles which in adjoining crests face in opposite directions, with crossbars connecting the spaces on alternate sides of each ridge. The rectangular type consists of two sets of ridges intersecting at right angles.[153]

Interference ripples come into existence whenever there is a sharp change in the direction of the wind so that the formation of wave ripple mark is continued at an angle to the original trend. This can be shown by simple experiment. The common occurrence of interference ripples in small ponds is thus accounted for.

Interference ripples seem to develop as a result of ordinary waves breaking up into two sets of oscillations crossing each other. Favorable conditions are furnished about the ends of bars, stranded logs, the angles of piers, and in small ponds. Ripple mark of this character is very common in shallow ponds and ordinarily may be seen by hundreds in the small ponds made by steam-shovel mining in the coal fields of southern Indiana. Originally they were considered tadpole nests, Hitchcock distinguishing two types, those of the Connecticut Valley sandstone being named *Batrachoides nidificans* and those of the Niagara limestone *B. antiquor*[154] (fig. 88).

COMPOUND RIPPLES.[155] A great variety of forms of complex rippling owe their origin to the simultaneous interference of wave-oscillation with current

[151] Analogous to that shown on a sand ridge of different origin on the beach of Lake Ontario, see Fairchild, H. L., Beach structure in Medina sandstone, Am. Geol., vol. 28, 1901, fig. 10, pl. 5.

[152] Kindle, E. M., op. cit., 1917, p. 31.

[153] For illustration of the rectangular type, see Kindle, E. M., op. cit., 1917, pl. 23, Fig. C; of the hexagonal type, figs. 8 and 17.

[154] Kindle, E. M., Origin of "Batrachoides the Antiquor," Geol. Mag., vol. 51, 1914, pp. 158–161.

[155] For illustrations, see Kindle, E. M., op. cit., 1917, pls. 14, 28, 29. See also p. 174, the effect of a gale on tidal meta-ripples.

action. All seem to be characterized by a systematic breaking or offsetting of the crests of the current-ripples. A systematic discussion of these forms, to which the term "compound ripples" might well be applied, is impossible at the present time, since practically no observations are available of the factors entering into their formation, or even of the forms themselves.

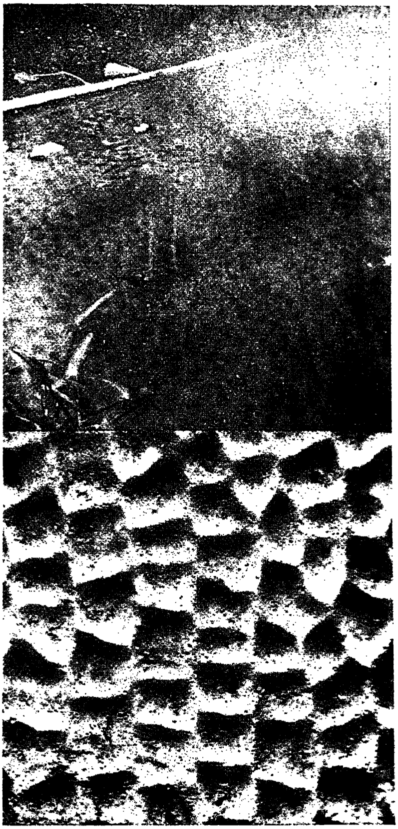


FIG. 88. "TADPOLE NESTS" (TOP) AND INTERFERENCE RIPPLE (BOTTOM)
Photograph by Doctor E. M. Kindle

Vertical Range of Ripple Mark

The discussions of ripple marks found in many texts and treatises on general geology treat them as shallow-water features, and this inadequate and inaccurate conception is reflected in the casual references to ripple mark in numerous geological papers.

In considering the maximum depth at which ripple mark may occur it is important to discuss separately the two classes of subaqueous ripple marks which have been described. The wave ripple mark will certainly be developed on sandy beds at any depth to which the effective oscillatory movement of waves extends. In the case of current ripple mark, the only factors essential to its formation are current action and suitable bottom material. There are no reasons why both of these may not be found at any depth known in epicontinental waters.

CURRENT RIPPLE MARK. The vertical range of current ripple is coincident with that of currents strong enough to move sand or silty deposits. There is now on record an abundance of data showing that current action is an occasional, if not a common, phenomenon of the sea bottom at considerable depths. In the Skagerrak, for instance, "the tidal currents are scarcely noticeable in the upper water layers, whereas they have been met with there down at the very bottom at such great depths as 200 m." Measurements made on the "Michael Sars" are interesting in this connection. On the edge of the continental slope, about 80 km. northwest of Aalesund on the Norwegian coast[156] in the open ocean, not in any channel, the Atlantic current was found running, on the average, parallel with the continental slope, at times with a velocity of 0.215 m. per second at a depth of 250 m. The lowest velocity observed was 0.059 m. per second. "This velocity is so great that the water would move grains of sand, and wash them away from the bottom, which at this place was rocky."[157] A velocity of 0.214 m. per second is sufficient to move sand, according to the observations of Forbes quoted by Nansen,[158] and consequently to produce ripple mark. Nansen concludes that the continental slope off the Norwegian coast "where it is sufficiently steep and exposed to the open ocean is swept by currents sufficiently rapid to wash clayey deposits and mud down into depths of 600 or 700 m."[159]

Verrill[160] has noted evidence of currents strong enough to move sand on the continental shelf off the New England coast at depths of 65 to 150 fathoms. South of the Azores Hjort[161] found considerable tidal currents down as deep as 800 meters.

[156] Report Norwegian Fishery and Marine Investigations, vol. 2, no. 1, 1909, p. 79.

[157] Helland-Hansen, B., and Nansen, F., The Norwegian Sea, Rept. Norwegian Fishery and Marine Investigations, vol. 2, no. 2, 1909, p. 155; also table on page 778.

[158] Nansen, F., The bathymetrical features of the North Polar seas, The Norwegian North Polar Expedition, vol. 4, No. 13, 1904, p. 139.

[159] Nansen, F., op. cit., p. 144.

[160] Verrill, A. E., Marine faunas off the New England Coast, Am. Jour. Sci., vol. 24, 1882, p. 449.

[161] Hjort, J., The "Michael Sars" North Atlantic Deep-Sea Expedition, Geog. Jour., vol. 37, 1911, pp. 349–377.

It is clear from the abundant evidence of current action in deep water that current ripple mark may be formed at great depths, and that it probably is formed on favorable areas at all depths within the limits of the continental shelf.

WAVE RIPPLE MARK. Oscillation ripple mark has a much more restricted bathymetric range than current ripple. There can be no doubt, however, that oscillation ripples form at considerable depths. There is reliable evidence, according to Hunt, "that at depths of about 40 fathoms in the English channel and of 50 fathoms on the Banks of Newfoundland, there is not only motion at the bottom, but strong motion, far exceeding the gentle oscillation of the water that is sufficient to ripple a sandy sea bed."[162] We have the testimony of Wharton[163] that fine mud and sand may be moved to a depth of 80 fathoms by wave action, and that there is evidence of the chafing of cables to a depth of 260 fathoms.

The observations of Siau[164] appear to indicate that ripple mark formed by wave action occurs at a depth of 188 meters near St. Gilles, Island of Bourbon (Réunion) in the Indian Ocean.

Nansen[165] has cited a number of records of wave action at considerable depths, among which are the following: "Aimé has proved by experiments that the waves with a height of 1.5 m. may cause considerable horizontal oscillations (70 to 80 cm.) at a depth of 14 m., and in the road of Algier, 1 kilometer from the shore, he could prove the occurrence of appreciable oscillatory motion at a depth of 40 m."[166] Cialdi states that in 1831 during the diving work on H. M. S. "Thetis" which had been wrecked at Cape Frio on the Brazilian coast, the diving bell at depths of 18 to 20 m., always during strong wind and not seldom in comparatively calm weather, was subject to violent horizontal oscillations of 1.5 m. amplitude, which made the work very dangerous to the divers.[167] Herman Fol states from his own experience that in the Mediterranean the task of the diver becomes very difficult, and when a "swell" is on, "an irresistible force makes him oscillate like a pendulum." "This see-saw motion of the water is felt nearly as much at 30 m. as at 10 m. of depth." Cialdi asserts that the movements of waves may disturb fine sand on the bottom at a depth of 40

162 Hunt, A. R., Proc. Roy. Soc. London, vol. 34, 1883, p. 15.

163 Wharton, W. J. L., Foundations of coral atolls, Nature, vol. 55, 1897.

164 Siau, M., De l'action des vagues à de grandes profondeurs, Compt. Rend., Acad. Sci., Paris, vol. 12, 1841, pp. 770–776.

165 Norwegian North Polar Expedition, vol. 4, 1904, p. 137.

166 Aimé, Ann. Chim. et Phys., Ser. d, vol. 5, 1842, pp. 417, et seq., quoted by Krümmel, O., Handbuch der Ozeanographie, 2nd ed., vol. 2, 1907, pp. 30–32.

167 Cialdi, Sul moto ondoso del mare, 2nd ed., Rome, para. 776, 1866, quoted by Krümmel, O., Handbuch der Ozeanographie, 2nd ed., vol. 2, 1907, p. 91.

m. in the English Channel, 50 m. in the Mediterranean, and 200 m. in the open ocean.[168]

The following observations pertain to wave length and amplitude. (a) When first appearing, oscillation ripples show a wave length which is half that of their full development.[169] (b) The wave length increases with the velocity of the current, that is, amplitude over period of the oscillation. De Candolle's and Darwin's experiments have shown that the increment of wave length is proportional to the increment of velocity. This law, of course, holds good only between two critical points of velocity, between which oscillation ripples, like current ripples, can exist. It cannot be reversed—that is, the wave length does not decrease with the velocity.

Darwin noted that "when once a fairly regular ripple mark is established, a wide variability of amplitude in the oscillation is consistent with its maintenance or increase." Forel demonstrated that any oscillation weaker than that which produced the ripple will not affect its orientation, even if its direction diverges from the original up to 45°.[170] This explains his observation that at the same locality, in the Bay of Morges, near the center of the north shore of Lake Geneva, the oscillation ripples never changed their direction during three months of observation, although waves reach the bay from all directions between east, south, and west. Their orientation corresponded to waves from the south, the direction of the strongest winds. At the shore they swung into parallelism with the shoreline.[171]

Since the amplitude of the oscillation at the bottom of the water body is a function of the height of the water wave above, this must bear a definite relation to the wave length of the ripples. It is not impossible that this relation one day will be utilized for a direct determination of the decrease of the wave amplitude with depth. At present, practically no data comparing amplitude of water waves and wave length of ripples are available, and a collection of such data would represent a distinct contribution to the study of ripples.[172] A number of measurements of wave length and amplitude have been compiled by Bucher.[173]

Forel's experiments and observations have shown conclusively that the

[168] Cialdi, op. cit., chap. 3. Quoted by A. Geikie (Text book of geology, 1882, p. 423) from Delesse, A., Lithologie des mers de France, 1872, p. 111.

[169] Darwin, G. H., op. cit., 1884, p. 23.

[170] Forel, F. A., op. cit., 1895, p. 263.

[171] Forel, F. A., op. cit., 1895, p. 270.

[172] The only observation of this kind that has come to notice is that by Stuchlik, H., which shows the wave length of the ripple equalling one-half of the amplitude of the wave under the conditions given in his Table V. Cf. Gilbert's statement (Ripple marks and cross bedding, Bull. Geol. Soc. Am., vol. 10, 1899, p. 138) "that at the most the ripple marks are only half as broad as the waves rolling above them are high."

[173] Bucher, W. H., op. cit., 1919, p. 197.

wave length diminishes with increasing depth of water. It should be noted however, that with relatively strong waves "for moderate depths the size of ripples is not very sensitive to variation of water depth," as observed by Gilbert on the bed of Lake Ontario.[174]

Experimental data led Ayrton to conclude that both amplitude and wave length are greater for wave ripple mark made in storms than in calm weather, and that the slopes on the shore side are steeper than those on the water side.[175] With both of these generalizations the observations of Kindle[176] are at variance.

In a series of observations[177] made along the shore of Lake Ontario near Wellington, Ontario, Kindle found a regular increase of the wave length with depth. He found in water:

Less than ½	foot deep, ripples 1 to 2	inches long
Less than 1¼	feet deep, ripples 2 to 4	inches long
Less than 2½	feet deep, ripples 3½ to 4	inches long
Less than 10	feet deep, ripples 4 to 6	inches long
Less than 11	feet deep, ripples 4½	inches long
Less than 20	feet deep, ripples 4 to 5	inches long

This directs attention to a factor which is of some importance in connection with the interpretation of fossil ripples. The waves which produced a velocity sufficient to form ripples of 4 to 5 inches wave length at a depth of 20 feet, had, of course, a higher orbital velocity at the depth of 2 feet. This velocity ought to have produced ripples of larger wave length, since 5 inches (12.7 cm.) probably was not the greatest wave length possible on the sediment in question. According to Forel's observations, such large ripples, if ever formed, would persist, and hence their general absence is good evidence that they never formed. We are, therefore, led to the conclusion that above a certain minimum depth a given bottom oscillation of a water wave will not produce ripples. This is probably due to the abnormal conditions of flow resulting from the "breaking" of the wave. Moreover, in shallower water, only smaller waves will produce ripples of smaller wave length. Consequently, along a gently sloping shore we should theoretically expect to find at first a rather rapid increase of the wave length of the persisting ripples to a certain depth, and then a very gradual decrease down to very small size. Small ripple marks may thus form in both shallow and deep waters, and their occurrences are, therefore, no indication of depth.

[174] Gilbert, G. K., op. cit., 1899, p. 138.

[175] Ayrton, H., The origin and growth of ripple mark, Proc. Roy. Soc. London, ser. A vol. 84, 1910, pp. 285–310.

[176] Kindle, E. M. op. cit., 1917, p. 28.

[177] Kindle, E. M., op. cit., 1917, p. 29.

On the other hand, wave ripple mark with large amplitude and wave length certainly cannot form in very shallow waters for the reason that large waves cannot develop to form them.[178]

Ripple mark observed by Kindle on the west side of Point Pelee, Lake Erie, displayed in two adjacent belts sharply contrasted wave lengths where the water depth ranged only from 18 inches to 26 inches. The near-shore belt in this case showed a wave length of 6 inches to 8 inches across a zone 7 or 8 feet wide which was followed by ripple marks spaced at 3 inches to 4 inches and extending lakeward an undetermined distance. These two sets of oscillation ripples in water of the same depth, one having a wave length twice that of the other, indicate the operation of factors other than depth in some situations which cannot at present be evaluated.

Ripple Mark on Calcareous Sediments

With few exceptions, the published observations on ripple mark of recent deposits relate to quartz sand. In subtropical and equatorial latitudes, calcareous sand frequently entirely supplants quartz sand on the beaches and in offshore waters. The specific gravities of the two kinds of sand are essentially the same, and they appear to react to wave and current action in much the same way.

The waters adjacent to Providence Island in the Bahamas afford good opportunities to see ripple mark on calcareous sand at localities easily accessible from the city of Nassau. The channel between Hay Island and Providence Island, with a depth of $1\frac{1}{2}$ to 3 fathoms, furnishes conditions favorable to the development of tidal currents of varying velocities between Nassau and the coral reefs 4 miles east, where the currents are strong enough to keep the limestone bottom swept clean of calcareous sand.

Between the reefs and west of the east end of the island considerable stretches of the bottom are covered with white "sand" consisting largely of coarse shell fragments. This "sand" is marked by ordinary current ripple mark of short wave length. Over the easterly part of the white sand bottom, where the currents probably have their maximum strength, the bottom is covered with sand waves or meta-ripples. These have a wave length estimated at from 15 to 20 feet and an amplitude of 6 to 8 inches.[179]

The waters of Biscayne Bay, Florida, furnish a considerable area of white calcareous sand bottom under water sufficiently shallow (12 to 18 feet) to permit careful inspection from a glass-bottomed boat. Asymmetric ripple mark with rather long wave length was observed near Cape Florida. A short distance from the steamer landing on the west side of the Cape,

[178] *Johnson, D. W.,* Shore processes and shoreline development, 1919, p. 512.
[179] These observations were made by Doctor Kindle on December 13, 1920.

parallel ridges of the sand-wave type were seen spaced 25 to 50 feet apart. In the deeper water, highly irregular bottom features occur somewhat comparable in complexity of pattern to the flat-topped sand ridges at Annisquam, Massachusetts, illustrated by Kindle.[180]

Fossil ripple mark is met with less frequently in limestones than in sandstones, but it is by no means a rare phenomenon. Small ripples are quite common in the Richmond formation of Ohio and Kentucky, and occur not infrequently in the Eden formation. They are also common in the Monroe formation of Adams and Highland counties, Ohio. Ripple mark of unmistakable current-ripple type, with a wave length of $1\frac{1}{4}$ inches and an amplitude of 1/8 inch, is represented in the Canadian Geological Survey collections by a specimen from the Upper Devonian limestone of the Hay River section, Northwest Territory, collected by E. J. Whittaker. Miller[181] states that small ripple marks with a wave length of 1 to 2 inches and an amplitude of $\frac{1}{2}$ inch occur at several horizons in the Pamelia, Lowville, and Trenton. Most of the ripple mark in limestone reported in geological literature, however, has a wave length of from 1 foot to nearly 7 feet. The numerous examples of Paleozoic ripple mark described by Prosser include both symmetrical and asymmetrical ripples, but all are forms with long wave length, generally from 20 to 36 inches. In several cases they are described as "clearly asymmetrical,"[182] or with "slopes steeper to the west than to the east," thus leaving no question as to their current origin. In other cases Prosser found "no difference in the slope," and Udden[183] notes limestone ripples with large wave lengths which are "slightly unsymmetrical." Bucher[184] has brought together measurements of a number of limestone ripples with large wave lengths which are "nearly symmetrical" (para-ripples), and he raised the question whether the formation of such large ripple mark is possible by wave action.[185] It may be that the para-ripples represent meta-ripples sufficiently modified by wave action or reversed tidal currents to have lost their original asymmetry.

Interpretation of Fossil Ripple Mark[186]

USE IN DISCRIMINATING BETWEEN UPPER AND LOWER SURFACES OF STRATA. Oscillation ripples are strictly symmetrical and generally have

[180] Kindle, E. M., op. cit., 1917, pl. 45.

[181] Miller, W. J., Geology of the Port Leyden Quadrangle, Lewis County, N. Y., Bull., 135, N. Y. State Mus., 1910, p. 36.

[182] Prosser, C. S., Ripple marks in Ohio limestones, Jour. Geol., vol. 24, 1916, p. 459.

[183] Udden, J. A., Notes on ripple marks, Jour. Geol., vol. 24, 1916, p. 125.

[184] Bucher, W. H., op. cit., 1919, p. 260.

[185] Bucher, W. H., op. cit., 1919, pp. 262–263.

[186] The work of Professor Bucher except for part of first paragraph.

sharp angular crests separated by wide rounded troughs which may show a low ridge in the center. The negatives of such ripples correspondingly show broad rounded crests (possibly with a narrow median groove) separated by sharply cut V-shaped troughs. These characteristics, when fully developed and well preserved, afford certain and easy criteria for the determination of the original order of superposition of strata. It frequently happens, however, that both the crests and troughs of oscillation ripple mark are rounded as in figure 4 A of Kindle's[187] ripple-mark profiles. In such cases determination of order of superposition from ripple-mark profile is impossible. But in the more normal examples with wide troughs and angular crests (figs. B and C), ripple mark yields unequivocal evidence as to order of superposition of beds.

PALEOGEOGRAPHIC INTERPRETATION. Each ripple offers some positive information concerning the physical conditions under which it was formed. In reasoning from the data contained in sedimentary rocks back to the highly complex conditions to which they owe their existence, this information is always valuable and often of crucial significance. The basic inferences that can be drawn from ripples may be tabulated, as follows:

1. Ripples of large wave length (measured in feet). ("Meta-ripples," highly asymmetrical, and "Para-ripples," less asymmetrical and even symmetrical.) Originate only through *currents of relatively high velocities*.[188]
   (a) If the wave length of such large ripples varies greatly from point to point on the same surface, and if the individual rippled layers cannot be traced for any great distance, the velocity of the current that produced the ripples must have varied greatly from point to point and must have been limited to a relatively small area, as is the case in river (or estuary) channels.
   (b) If, on the other hand, the wave length of such large ripples is remarkably uniform on any given surface, and if such a rippled layer can be traced for relatively great distances (say over several square miles), conditions necessary for this formation are probably found only in arms of the sea agitated by tidal currents.[189]
2. Asymmetrical ripples of small wave length (measured in inches) merely indicate the existence of currents of lower velocity than 1.
   (a) A ratio of amplitude to wave length of 1:4 to 1:10 is characteristic of water-formed ripples.

[187] Kindle, E. M., Recent and fossil ripple mark, Mus. Bull. No. 25, Geol. Surv. Canada, 1917, fig. 4.

[188] For quantitative data concerning all forms of ripples, see Bucher, W. H., 1919.

[189] It seems improbable that wind-drift in land-locked bodies of water can obtain sufficient strength to reach the bottom velocities necessary for the production of such large ripples. No such case has been recorded. Wind-drift, however, is capable of strengthening or weakening tidal currents.

(b) A ratio of amplitude to wave length of 1:20 to 1:50 (or over) is characteristic of wind-formed ripples.

(c) Linguoid current ripples form only under subsiding water of vanishing depth, that is, on flood plains and tidal flats.

3. Symmetrical (oscillation) ripples (always of small wave length measured in inches), both of simple and polygonal interference pattern, form only under water in the absence of currents at the time of their formation.

4. Ripples of any kind may be absent from a given formation, either because they were not formed during the deposition of the sediments, or because they were not preserved. Ripples do not form:

(a) Where the required current or oscillatory motion is lacking or does not touch the bottom with sufficient strength;

(b) Where the sediment is too coarse or too fine to form ripples;

(c) Where vegetation (for instance, water weeds) prevents uniform action of the currents on the sedimentary surface.

Ripples are not preserved:

(d) Where conditions favoring the rapid covering of the ripples are absent.

The use of the basic data in paleogeographic interpretation is illustrated by the following two examples. In the cases chosen, reasoning from the observation on ripples alone leads to remarkably definite results, which can always be tested by independent lines of reasoning based on other characters of sediments. It is from the convergence of such independent lines of thought that we derive the degree of probability approaching certainty which is our aim. In these examples we shall limit ourselves to the observations on ripples, referring by numbers and letters to the preceding tabulation.

Example 1. Fossiliferous limestone layers alternating with shales; pararipples on many layers, some traceable over large areas; small current ripples common; oscillation ripples present, but relatively rare (Richmond group of Ohio, Kentucky, and Indiana).

These are sediments laid down in an arm of the sea in free communication with the ocean and agitated by tidal currents (1, b); deep enough to allow sufficient sediment to be thrown into suspension to cover the ripples when the agitation of the water has ceased (4, d); shallow enough to allow waves to act on the bottom during periods of slack water (3); the depth depending on the size of the waves which, in turn, is determined largely by the "fetch" of the wind, that is, the size of the water body.

Since the time of slack water between tides is relatively short, oscillation ripples are relatively rare.

Example 2. Unfossiliferous fine-grained sandstones interstratified with more or less shaly portions; oscillation ripples abundant, all other types absent; most ripples of nearly the same strike (N.53°W.), which remains

constant over an area 115 miles long and 20 miles wide. (Bedford and Berea formations at the base of the Mississippian section of eastern and central Ohio.)[190]

Formed in a body of water not in free communication with the ocean, that is, in a land-locked arm of a sea or a lake, as shown by the complete absence of currents; the parallelism of the ripples indicates that in one direction larger waves formed than in all others, either because the shape of the water body gave the wind sufficient fetch only in one direction, or because strong winds blew practically in one direction only (or two co-linear directions) as, for instance, in the case of monsoons.

In the case of the Bedford-Berea ripples, a widespread unconformity between the Bedford and Berea formations to the north, which is absent in the south, seems to indicate that the trend of the ripples was independent of changes in the form and size of the water body. It seems probable, therefore, that their parallelism is due to the dominance of one wind direction over all other, that is, probably to monsoon winds.[191]

CURRENT MARKS

Current mark is a term which may be applied to irregular structures on bottoms showing current-erosion effects. A current mark which is common on some tidal mud flats uncovered at low tide is made by the aggregation of the retiring waters into channels, with the result that the surface becomes eroded into rectangular, triangular, etc., high places separated by these channels. Such were observed in splendid development in Ellis Bay on Anticosti Island, the elevations being 4 to 5 inches high and 2 to 70 feet across. After becoming covered by succeeding sediments, the channel fillings in some instances resemble casts of logs.

Another type of current mark is made on the lee side of an obstruction where the force of the water is intensified and it erodes a small depression. This is commonly seen on a beach where the returning water erodes on the lee side of a shell or pebble (fig. 89).

[190] Hyde, J. E., The ripples of the Bedford and Berea formations of central and southern Ohio with notes on the paleogeography of that epoch, Jour. Geol., vol. 19, 1911, pp. 257–269.

[191] Other important references relating to ripple mark are the following: Brown, A. P., The formation of ripple-marks, tracks, and trails, Proc. Acad. Nat. Sci., Philadelphia, vol. 63, 1911, pp. 536–547; Dodge, R. E., Continental phenomena illustrated by ripple marks, Science, vol. 23, 1894, pp. 38–39; Hunt, A. R, Description of oscillation ripples, Proc. Roy. Soc. Dublin, vol. 4, 1884, pp. 261–262; The new question of ripple mark, Geol. Mag., vol. 41, 1904, pp. 619–621; Jagger, T. A., Some conditions of ripple-mark, Am. Geol., vol. 13, 1904, pp. 199–201; Lemoine, P., Les ripple-marks, Nature, 1917, pp. 204–206.

MISCELLANEOUS STRUCTURES MADE BY WAVES

Swash Mark

Waves breaking on a gently sloping beach lead to a part of the water gliding up the slope as a thin sheet. This is known as the swash.[192] Its line of farthest advance is the place of total loss of beach-directed energy,

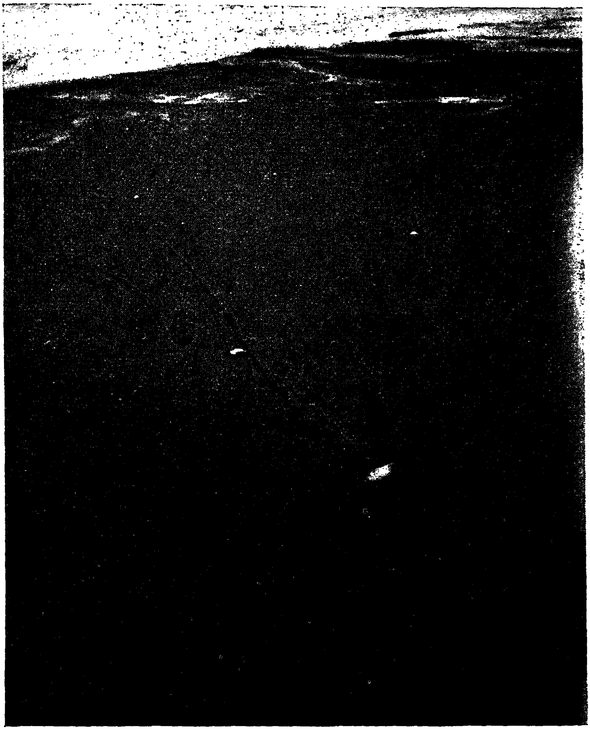


FIG. 89. CURRENT MARK

The sea is in the background. The obstruction to which the mark is due is visible on the end of the mark near the bottom of the picture. Photograph by W. H. Twenhofel of mark on the beach near the mouth of St. John River, north shore of the Gulf of St. Lawrence, Quebec Labrador.

and there its load is partly dropped, leaving a small wavy ridge consisting of fine sand, mica flakes, pieces of seaweed, and other vegetable matter. This is the swash mark. The different swash marks form an irregular network of fine lines or ridges, each more or less convex toward the land, and in some instances a dendritic pattern is developed (fig. 90). Markings which

[192] Johnson, D. W., Shore processes and shoreline development, 1919, p. 514.

appear to be of this origin have been described from the Portage of New York,[193] and wave lines are stated to be "frequent in great perfection on the smoother flags" of the Medina sandstone.[194]

Another type of mark made by waves is the miniature terrace and cliff effect eroded on a beach of sand or other fine material during low tide or any stationary position of the water level. These are occasionally well shown on the large ripples of tidal estuaries. They can form only above water and have a poor chance of preservation. They do not appear to have been observed in the geologic column.

FIG. 90. SWASH MARK
The sea is on the left. Photograph by W. H. Twenhofel. Between Long Point and mouth of St. John River, north coast of the Gulf of St. Lawrence, Quebec Labrador.

Rill Mark

Each high tide or each advance of a wave saturates the sands and muds covered. On the retreat of the wave or tide, water may drain from the sands and muds and aggregate itself into rills in a narrowly dendritic pattern,

[193] Clarke, J. M., Strand and undertow markings, etc., Bull. 196, New York State Museum, 1917, pp. 199–238.

[194] Fairchild, H. L., Beach structure in Medina sandstone, Am. Geol., vol. 28, 1901, p. 10.

the rills being 2 to 10 mm. wide. These erode small channels on the surface. The same feature may be developed on any inclined body of sand or mud after it has been uncovered by retreat of water. Dodge[195] has described occurrences of small dendritic rills on the seaward slopes of ripples of 18 inches amplitude, and their occurrence is common on most shores of suitable material. Patterns of similar character develop where small streams debouch on a flat sandy or clayey surface. The distributaries spread away from the main stream, and as they advance the water is absorbed and ultimately disappears.[196]

Each rill pattern or system is rarely more than a couple of feet long and from a fourth to a third as wide, the tendency being to narrowness. Fossilized, they resemble plants, and it is possible that some of them have been so considered, as pointed out by Nathorst[197] and Williamson.[198]

On beaches composed of fine sands, the returning waters of waves may be succeeded by a net-work of anastomosing rills or small currents whose minute erosion produces a sculpturing of the beach surface resembling the surface pattern of a *Lepidodendron* tree, the uneroded surface or polygons between the minute currents being diamond-shaped, with the long axes of the diamonds normal to the water's edge. The diamond-shaped polygons approximate 12 to 25 mm. wide and 25 to 50 mm. long; the minute channels are less than 1 mm. deep. These may be the "ripple marks" that resemble the "overlapping scales of a ganoid fish" (p. 655). Marks of this character have been seen on many miles of beaches about the Mingan Islands, the Atlantic Coast about Cape Henry, and on beaches of California south of San Francisco and they probably are present on most sand beaches.

As the various varieties of rill mark are made above water, they have the same chances of preservation and the same significance as other marks made under like conditions. Occurrences in the geologic column should be rare.

Beach Cusps

Beach cusps are large anticlinal shaped structures which project outward from the shore and are composed of materials ranging from sand to cobbles. According to Johnson,[199] the ideal beach cusp has a shape suggesting an

[195] Dodge, R. E., Continental phenomena illustrated by ripple marks, Science, vol. 23, 1894, pp. 38–39.

[196] Grabau, A. W., Principles of stratigraphy, 1913, p. 708.

[197] Nathorst, A. G., Om några förmodade växtfossilier, Öfv. Köngl. Vet. Akad., Förhandl., vol. 30, 1873, pp. 25–52.

[198] Williamson, W. C., On some undescribed tracks of invertebrate animals from the Yoredale rocks, and on some inorganic phenomena, produced on tidal shores, simulating plant-remains, Mems. Manchester Lit. and Philos. Soc., vol. 10, 1887, pp. 19–29.

[199] Johnson, D. W., op. cit., 1919, p. 463.

isosceles triangle with its base parallel to the shoreline and its apex extending into the water. The angle between the "equal" sides of the triangle may be large or small, making the cusp wide or narrow. Ordinarily the sides are curved, and the curving may be either convex or concave outward. They may gradually merge without distinction into the beach or be sharply set off therefrom. The heights may be such as not to vary appreciably from the beach slope, or they may rise several feet above the beach level, the highest point of the cusp being located at any point. Lengths range from a few feet up to about a hundred. Johnson records the occurrence of cusps on Long Island with distances from apex to base of 20 to 30 feet and with 75 to 90 feet between apices of adjacent cusps. Kemp[200] has described cusps from Florida which were 90 to 95 feet from base to apex and 3 to 4 feet high. Beach cusps usually extend straight out into the water, and the slopes, unless wave-eroded, are symmetrical. They are more or less equally spaced along beaches and somewhat resemble large ripple marks.

There does not appear to be agreement respecting the origin of beach cusps. Johnson's explanation is as follows:

> Selective erosion by the swash develops from initial irregular depressions in the beach shallow troughs of approximate uniform breadth, whose ultimate size is proportional to the size of the waves, and determines the relatively uniform spacing of the cusps which develop on the inter-trough elevations.[201]

Whatever the origin, structures of this character seem to develop only on beaches, where they form ridges at right angles to the shoreline.

The fairly sharp-crested ridges of symmetrical profile described by Gilbert[202] and Fairchild[203] from the Medina sandstone of New York may be fossil beach cusps. Gilbert considered them giant ripples made by waves with a probable height of 60 feet, but in view of the type of sediments in which they occur, this explanation is an impossible one. Branner[204] suggested that the "giant ripples" might be fossil beach cusps. Fairchild assigned them to a beach origin.

STRUCTURES MADE BY FLOATING OBJECTS

Objects floating in the water—ice, logs, trees with limbs attached, seaweeds, grass, small shells, living animals, etc.—develop markings on the

[200] Kemp, J. F., cited by Johnson, D. W., op. cit., 1919, p. 466.

[201] Johnson, D. W., op. cit., 1919, p. 481.

[202] Gilbert, G. K., Ripple-marks and cross-bedding, Bull. Geol. Soc. Am., vol. 10, 1899, pp. 135–140.

[203] Fairchild, H. L., Beach structure in Medina sandstone, Am. Geol., vol. 28, 1901, pp. 9–14.

[204] Branner, J. C., Ripples of the Medina sandstone, Jour. Geol., vol. 9, 1901, pp. 535–536.

muddy bottoms with which they come in contact. These floating objects, dragging on the bottom, produce a great variety of markings.

Floating objects moving in one direction produce straight grooves on bottoms which they touch, the grooves ranging in dimension from those that are deep and wide to thread-like scratches. If a floating object pursues a curved path, curved markings result; if it rotates around a vertical axis while moving in a given direction, sinuous markings develop. Objects whirled in eddies produce circular and elliptical markings. A tree with many limbs dragging on the bottom may leave a well marked multiple trail in its wake.

In very shallow waters, small floating dead shells may become responsible for many trails. These may be developed in laboratory experiments by using the shells of *Limnæa* or *Planorbis*, two common lake shells, and placing them in water of a few millimeters depth. After a few days the bottom will be found covered with markings which cross and recross in the manner of worn trails.

Most marks developed in these ways are probably limited to shallow water; water of 8 to 10 feet depth would include most of them. From this generalization, however, markings made by icebergs and some floating seaweeds should be excepted. Ice may scratch the bottoms for depths of several hundred feet. Some of the seaweeds are very long, the giant kelps of the North Atlantic rivaling forest trees in this respect, and these, with rocks still grasped in their holdfasts, may scratch the bottom to depths of about 100 feet. Some have great floats which enable them to travel long distances.

Markings arising from floating matter may occasionally be seen in great development on lake and sea bottoms, and their occurrence in the geologic column should be not uncommon. As the markings usually are made in mud which ordinarily weathers before it reaches the surface, their best chance of preservation exists where muds become covered with sand or lime sediments. Counterparts of the markings on the mud are then made on the underside of the overlying beds.

Clarke[205] has described beautiful examples of straight ridges found on the undersides of hard flaggy sandstones in the Portage of New York. The photographs suggest glacial grooves and ridges, but it is not likely that they would be mistaken for such, as the surfaces are not polished. Clarke suggested an origin due to floating ice.

Powers[206] found similar markings preserved on the undersides of Penn-

[205] Clarke, J. M., Strand and undertow markings, etc., Bull. 196, New York State Museum, 1917, pls. 15–20.

[206] Powers, S., Strand markings in the Pennsylvanian sandstones of Osage County, Oklahoma, Jour. Geol., vol. 29, 1921, pp. 66–80.

sylvanian sandstones in Texas and Osage County, Oklahoma. The markings are extremely abundant on some slabs, a photograph of one $5\frac{1}{2}$ feet wide showing 48 ridges, representing as many grooves in the underlying rock. Many of the markings figured by Powers could have been made only by floating flexible objects, and they suggest that fronds of dendritic algæ or branches of land plants were being dragged by a sinuous current over a mud surface. In some cases the marks diverge, suggesting that currents separated drifting objects.

Objects floating in water and rising and falling with the waves might come in contact with the bottom while in the troughs and be above it on the crests. An object floating from shallow to deeper water might drag bottom for a space, but after getting over deeper water would touch the bottom only while in the troughs of the waves. Its path would thus be indicated on the bottom by a continuous trail for a space, then by a series of pits. Seaweeds floating with holdfasts weighed down with rocks might cover the surface of a mud bottom with pit-like markings. Dr. J. B. Woodworth[207] stated that the tentacles of a floating jellyfish also make pits in this fashion.

MARKINGS MADE BY BASALLY ATTACHED PLANTS

Areas covered with loose material and having a sparse growth of plants, either above or below water, may show an abundance of markings of concentric curves. A plant usually is found with its branches or leaves in contact with the markings, and it is to the waving of this plant that the markings are due. Each portion of a plant touching mud or sand develops an impression which is an arc of a circle. Extremely delicate plant structures make them, and as they occur abundantly on existing surfaces, they should occur over similar surfaces of the past. Structures more or less similar which have been described as *Taonurus* or *Spirophyton* have been considered plant structures by some and by others as mechanically or organically produced.[208] Whatever they may be, it is certain that very similar structures are of the origin given above.

TRACKS AND TRAILS

Throughout all zoologic history, animals have left tracks and trails on the muds and sands over which they moved. Some of these show the contests of animals with each other, and still others their struggles in the agonies of death. Some "tracks" are exceedingly difficult to differentiate from markings made by inorganic agencies.

[207] Personal communication.

[208] It does not seem possible that the *Taonurus* in the New Providence shale of Kentucky could have been produced as described in this topic.

A discussion in detail of the different kinds of tracks would mean pages of description to little end in this connection. They consist of worm trails from the rocks of all ages since the Proterozoic; tracks of crustaceans, as perhaps *Climatichnites* from the Cambrian of Wisconsin, which resembles the trail of a small automobile and may be an algal impression, and double rows of pits, as in the Richmond of Anticosti, where they have been followed over a 6-inch bed of limestone for 75 miles; tracks of amphibians from the Kansas Coal Measures; and the famed reptile tracks of the Newark sandstone.

The rocks of many horizons are marked by the holes in which worms or other organisms lived. These may be vertical, as *Scolithus* of the Cambrian; transverse, or U-shaped, as *Arenicolites*[209] and *Arenicola*.[210] Not uncommonly the openings of the holes have small elevations about their entrances.

ICE CRYSTAL IMPRESSIONS

When wet mud or fine sand or other fine-grained sediment freezes, the water in the mud may become more or less segregated as ice crystals or needles on and within its upper portion. Similar but much coarser and less defined crystals form in medium- and coarse-grained sands. Crystals are better developed in sediments completely saturated with water than in those only partially saturated.[211] These crystals or needles are extremely common in springtime when the ground is saturated with water, but seem to be less common in the autumn. They are best shown on mud surfaces that are even and smooth. The lengths of the crystals approximate one-half inch, but occasionally some occur with lengths of one or more inches. They trend in many directions on a very small surface, occur irregularly isolated, intersect irregularly, and in many instances are arranged in bundles or radiate from a point. Most commonly they are straight, but some are curved. The greatest width generally is 1 to 2 mm. and not uncommonly the width is not greater than a thread. When ice melts a small groove remains to

[209] Coysh, A. W., U-shaped burrows in the Lower Lias of Somerset and Dorset, Geol. Mag., vol. 68, 1931, pp. 13–15; Salter, J. W., On annelid-burrows and surface markings from the Cambrian rocks of the Longmynd, Quart. Jour. Geol. Soc., vol. 13, 1857, pp. 199–205.

[210] Soergel, W., Spuren mariner Würmer im mittleren Buntsandstein (Bausandstein) und im unteren Muschelkalk Thüringens. Neues Jahrb. f. Min., Beil.-Bd. 49, 1923, pp. 510–549; Richter, R., Flachseebeobachtungen zur Paläontologie und Geologie VII–XI, Senckenbergiana, Bd. 6, Heft 3/4, 1924, pp. 119–140; Stather, J. W., U-shaped markings in estuarine sandstone near Blea Wyke, Proc. Yorkshire Geol. Assoc., vol. 20, 1923–1926, pp. 182–184; and Bather, F. A., U-shaped burrows near Blea Wyke, Ibid., pp. 185–199. Bather gives excellent illustrations and diagrams and a review of the literature.

[211] Allen, J. A., Ice crystal markings, Am. Jour. Sci., vol. 11, 1926, pp. 494–500; see also Marbut, C. F., and Woodworth, J. B., 17th Ann. Rept. U. S. Geol. Surv., 1896, pt. i, p. 992; and Powers, S., Strand markings in the Pennsylvanian sandstones of Osage county, Oklahoma, Jour. Geol., vol. 29, 1921, pp. 75–76.

FIG. 91. COUNTERPART OF ICE CRYSTAL IMPRESSIONS

Photograph of a counterpart made by pouring plaster over a mud surface in which ice crystals had formed and had then been removed by slow evaporation into the atmosphere, leaving depressions in the mud. The small ridges on the plaster cast have the forms and orientations of the ice crystals. After Doctor J. A. Udden.

mark the place of the crystal, and the surface has somewhat the appearance of having been minutely mud-cracked (fig. 91). Clarke has pointed out that a similar effect may be produced by spicular or anchor ice.[212]

Ice-crystal impressions are best made in clay or mud, but as clay usually is broken down before exposure, original ice crystals are not likely to be found. Counterparts may be found on the undersides of overlying beds, particularly sandstones.

Udden[213] has described markings interpreted as ice-crystal impressions from the Dakota sandstone of South Dakota and the Upper Cretaceous Eagle Ford shales of Texas.

On the undersides of flaggy sandstone from the Portage of New York, small rod-like markings, usually single, but occasionally in radiating sheaths, and generally of irregular orientation, were early figured by Vanuxem and Hall as *Fucoides graphica*. The dimensions range up to about an inch long and 1 to 2 mm. wide. Clarke[212] suggested that these markings developed from ice crystals formed in the muds on the bottom of the Portage sea in connection with ground or anchor ice.

RAIN, DRIP, AND HAIL IMPRESSIONS

Rain falling on wet mud of not too high fluidity produces circular or elliptical pits margined by ragged rims slightly elevated above the surrounding mud. The surfaces of the depressions are visibly rough. The rims are slightly higher and the depressions slightly deeper on the sides toward which the falling drops are directed, and the depths of the depressions vary with the size of the drops which make them, the force with which the drops fall, and the softness of the mud. Pits form but do not persist in very fluid mud. The maximum depths appear to be about 3 mm., and the widths range from about 2 to 12 mm. Rain also makes impressions on sand, but the rims are not so sharp as those bordering impressions made in mud. After many impressions have been made on a sand surface, it becomes sculptured by coalescing pits (fig. 92),[214] and upon this surface there may also be rill markings produced by draining away of the rain water. Rain impressions in the geologic column have been many times recorded, but it is extremely doubtful if they really occur so abundantly as the literature indicates. So many agents form somewhat similar pits or impressions that

[212] Clarke, J. M., Strand and undertow markings, etc., Bull. 196, New York State Museum, 1917, pp. 205–210, pls. 20–23. Clarke is stated to have later abandoned the view that *Fucoides graphica* represents ice crystal impressions, see Schuchert, C., Am. Jour. Sci., vol. 13, 1927, p. 159.

[213] Udden, J. A., Fossil ice crystals, Bull. 1821, Univ. Texas, 1918, pp. 1–8, ten plates.

[214] Wasmund, E., Rieselfelder und Blattfäckerabdrücke auf rezentem und fossilem Süsswasser-flachstrand, Senckenbergiana, Bd. 12, 1930, pp. 139–151, figs. 1–2, p. 143.

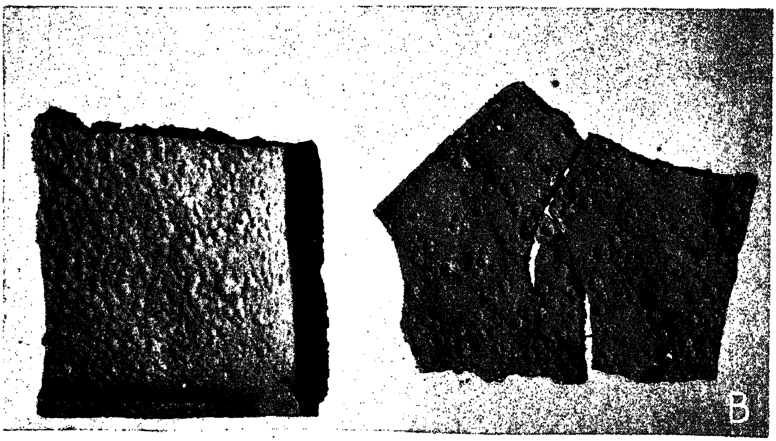


FIG. 92. *A*, BUBBLE IMPRESSIONS; *B*, RAINDROP IMPRESSIONS

The left illustration of *B* shows the coalescing pits produced by many drops. Photograph by Diemer, University of Wisconsin.

it is extremely likely that some of the supposed rain impressions are due to other causes.[215] The tendency has been to designate any circular impression a rain print.

Drip impressions (fig. 93) are like those made by rain, but the maximum and average widths appear to be greater. As water dripping from objects usually falls without a horizontal component, the tendency is for the pits to be circular.

Spray and splash impressions develop on beaches and shores where the wind drives spray against the mud and sand of the beach. The impressions are like those made by rain except that there is greater variation in dimen-

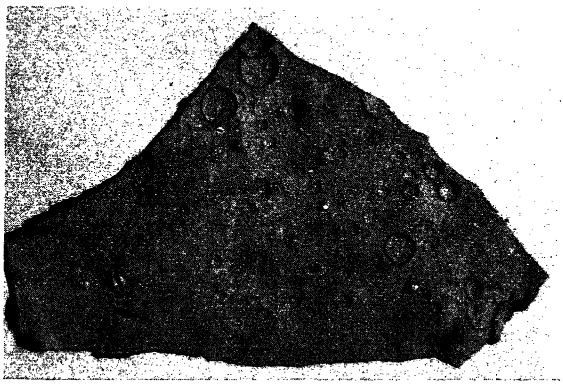


FIG. 93. DRIP IMPRESSIONS MADE IN THE LABORATORY
The scale is given by the small shells. Photograph by Diemer, University of Wisconsin

sion, and, as the horizontal component invariably is large, the impressions tend to be elliptical.

Hail impressions (fig. 94) are larger and have deeper and higher margins for the same character of mud and sand than do those made by water. Hailstones descending perpendicularly produce circular impressions; those coming down at a slant make elliptical impressions with greater depths and higher margins on the sides toward which the hailstones are directed. Impressions made by hail ought to occur in the deposits of the geologic column, but they do not appear to have been noted, except that Lyell pictures supposed hail prints from Triassic red shale of New Jersey. Hailstones with

[215] Lyell, C., On fossil rain-marks of the Recent, Triassic, and Carboniferous periods, Quart. Jour. Geol. Soc., vol. 7, 1851, pp. 238–247; Ibid., vol. 13, 1857, pp. 199–206; Andrée, K., Geologie des Meeresbodens, Bd. 2, 1920, pp. 91–92; Twenhofel, W. H., Impressions made by bubbles, etc., Bull. Geol. Soc. Am., vol. 32, 1921, pp. 369–370.

diameters of 62.5 by 50 by 31 mm. have been measured,[216] and hailstones as large as grapefruit and weighing 1½ pounds are stated to have fallen at Potter, Nebraska, on July 6, 1928.[217] Particles of these dimensions are able to make very large impressions.

Each of these marks except that made by hail is formed only on surfaces exposed to the atmosphere; hail may make impressions in very shallow water. Their finest development occurs on flood plains, deltas, and tidal flats like those of the Bay of Fundy.

FIG. 94. HAIL IMPRESSIONS MADE IN THE LABORATORY
The ice spheres were dropped from a height of about ten feet. Photograph by Diemer, University of Wisconsin.

PIT AND MOUND STRUCTURES[218]

Kindle[219] seems to have been the first American author to describe the structures designated "pit and mound," these structures developing in his experimental work in muds precipitated in salt water, the settling of the mud being accompanied by small upward currents therein. These struc-

[216] Bevan, A., Peculiar hail, Science, vol. 58, 1923, pp. 443–444.
[217] Blair, T. A., Hailstones of great size at Potter, Nebr., Monthly Weather Review, vol. 58, 1928, p. 313.
[218] Designated convection current impressions in the first edition of this book.
[219] Kindle, E. M., Small pit and mound structures, etc., Geol. Mag., vol. 3, 1916, pp. 542–547.

tures had been previously described by Hughes.[220] Later work by Twenhofel[221] proved that salt water is not essential and that exactly similar features develop in fresh water under conditions of rapid settling. The mechanics of formation have been given by Schofield and Keen.[222] When mud concentrations acquire a certain rigidity, small fissures develop which become filled with clear liquid whose density is less than that of the surrounding mud-laden liquid, thus setting up a circulation of upward currents in the fissures, while the surroundings sink. The fissures tend to close at the bottom and enlarge toward the top into conical chimneys through which

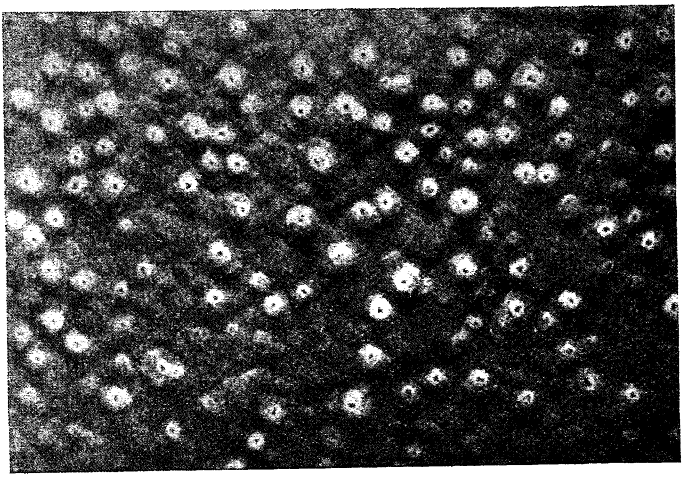


FIG. 95. PIT AND MOUND STRUCTURES

The little mounds are about 1 mm. in height and about 1 cm. across, each mound having a well defined hole at the summit. The mounds are determined by the development of slight rigidity of the upper part of materials settling from suspension. It is thought that the introduction of new material in suspension shortly after the pit and mound structures begin to form would give the structure known as landscape marble. After Schofield, R. K., and Keen, B. A., Rigidity in weak clay suspensions, Nature, vol. 123, 1929, pp. 492–493.

the upward motion of the liquid can be traced by small particles of mud held in suspension. These particles are deposited in a ring around the top of each chimney. Weaker suspensions settle until a layer is built upon the bottom which has the necessary concentration, following which the chim-

220 Hughes, T. McK., Quart. Jour. Geol. Soc., vol. 40, 1884, p. 183, pl. 11, fig. 6.

221 Twenhofel, W. H., Impressions made by bubbles, etc., Bull. Geol. Soc. Am., vol. 32, 1921, pp. 367–370.

222 Schofield, R. K., and Keen, B. A., Rigidity in weak clay suspensions, Nature, vol. 123, 1929, pp. 492–493.

neys develop. The critical concentration necessary for formation of a chimney increases with the coarseness of the suspended particles. Schofield and Keen state "that the critical concentration, even in the coarser suspensions is only about 1.5 per cent by volume." The small mounds are about 1 mm. high, range from 3 to 10 mm. in diameter, and each has a small crater-like depression on its summit with diameter approximating $\frac{1}{2}$ to 1 mm. (fig. 95). Cross sections of sediments in which currents of this type have developed strikingly resemble landscape marble, and it is possible that this latter structure originates in this way. These cross sections are readily seen in glass vessels in which mud concentrations are permitted to settle. The formation of landscape marble seems generally to have been ascribed to emanations of gas through sediments or to shrinkage attending consolidation.[223] Whatever the origin of landscape marble, it seems very probable that pit and mound phenomena can give rise to an almost identical feature.

Pit and mound structures probably develop in any depth of water. They should be common in the deposits of delta environments or others where conditions permit rapid settling.

BUBBLE IMPRESSIONS

Impressions made by bubbles[224] are of two types, depending on whether or not the bubble remains stationary after coming in contact with the mud surface. If a bubble becomes attached to the bottom, either being brought there by the weight of sediment settling on its surface, by becoming stranded, or by being expelled from the mud itself, mud settles on its surface for a while; but ultimately the bubble may rise to the surface of the water, leaving an impression which is a section of the bubble less than half its volume. The impressions ordinarily are not margined by raised rims, and the surfaces are smooth. So far as observed, diameters range from microscopic to about 7 mm., but it appears probable that greater diameters may be attained (fig. 92). The bubbles develop in the first place from gas produced in the sediments through decay of organic matter, through the expulsion of air held in the sediments, or as a consequence of some agitation of the waters.

Buckland[225] seems to have been the first to call attention to bubble impressions, and they were later noted by Lyell,[226] who described small con-

[223] Woodward, H. B., Remarks on the formation of landscape marble, Geol. Mag., vol. 9, 1892, pp. 110–114; Thompson, B., Landscape marble, Quart. Jour. Geol. Soc., vol. 50, 1894, pp. 393–410.

[224] Twenhofel, W. H., Impressions made by bubbles, etc., Bull. Geol. Soc. Am., vol. 32, 1921, pp. 369–370.

[225] Buckland, W., Rept. Brit. Assoc., 1842, p. 57.

[226] Lyell, C., op. cit., 1851, pp. 241–242.

vexities on the surface of mud due to small cavities made by bubbles, the mud having acquired rigidity before the bursting of the bubbles. Lyell also described circular pits made by bubbles rising in mud to its surface and there bursting.

Such impressions seem to be formed most abundantly beneath waters carrying a heavy burden of sediments. They may be seen on any recently flooded mud flats, on the surface of ice, and on the bottoms of water bodies.

Bubbles forming in muds and rising to the surface may leave impressions consisting of tubes which are margined at their upper ends by elevated rims. These have been experimentally formed in muds, with yeast used to form gas. The tubes resemble those known as *Scolithus*.

It is known that structures of this origin may form in shallow water, and it is probable that most of them originate under such conditions. Impressions made by gas expelled from muds may be developed on bottoms of any depth.

Compared with raindrop, drip, and spray and splash impressions, most of those made by bubbles are not margined by raised rims and have smooth surfaces, but these differences probably would be extremely difficult to detect in fossil form.

Bubbles wandering over the surface of very shallow water make shallow impressions where they come in contact with soft mud. Often these are of intricate pattern. Bubbles floating on the wave-agitated surfaces of waters but little deeper than the diameters of the bubbles may touch bottom in the troughs and rise above it on the crests. Each contact with a bottom of suitable materials may produce a circular pit. These are so shallow that it is doubtful if they could be preserved.

SAND HOLES

Closely related to bubble impressions are the sand holes made on sand beaches on the advance of a wave over a beach. The mechanics of their formations are as follows. The retreat of a wave leaves the sand saturated with water. This escapes to the surface on the lower part of a beach in seepage which frequently becomes aggregated into small rills, air entering the sands as the water escapes. The advancing wave expels the air by replacing it with water, the air reaching the surface of the sands on the upper part of the beach almost at the moment of wave retreat. The air escapes rather violently and leaves a pit which has a depth ranging to 7 or 8 mm. and a width a little less than the depth. The pits have raised margins.

Sand holes seem to have been first described by Bryson[227] in 1865, who referred their origin to sand-hoppers, and noted their resemblance to rain-

[227] Bryson, A., Surface-markings on sandstone, Geol. Mag., vol. 2, 1865, pp. 189–190.

drop impressions. Their first description in America was made by Palmer[228] in 1928, who gave the correct explanation of their origin. They have also been described by Deecke,[229] Högborn,[230] Andrée,[231] and probably others, and it has been suggested that some *Scolithus* tubes were thus formed.

Sand holes are extremely common on sand beaches, and the present author has seen them forming on Lake Michigan, the Gulf of St. Lawrence, the California coast, and elsewhere, each wave forming hundreds, the succeeding wave destroying these and forming others. Falling waters leave the beaches covered with thousands. These pits soon are taken possession of by sand-hoppers and perhaps other organisms, whence has arisen the opinion held by some that these organisms form the pits. It is possible that similar pits may so originate, but in all cases observed by the present writer, the sand-hoppers seem to have occupied holes formed as described above.

Occurrence of sand pits in the geologic column should be rare, but as they form in the same environment as swash mark, whose preservation is known, it seems probable that some "rain prints" may be sand pits.

SPRING PITS

Spring pits are made by springs reaching the surface through sands on beaches. Similar pits are made elsewhere, but as their chances of preservation are nearly zero, such are not considered. Only a single description seems to exist in the literature;[232] this is by Quirke, and the pits were studied on the shores of Maple Lake, Ontario. However, occurrences probably are common. The pits on Maple Lake shores are 1 to 3 feet or more apart, have funnel or bowl shapes, are usually less than 2 feet in diameter, and are about 6 inches deep of which 4 inches represents excavation and 2 inches fillings around the margins. The pits have the coarsest sands in their bottoms and the finest around the margins at the top. They form not only on the shore above water but also in the shallow waters adjacent to the shore. Their formation ends when water ceases to flow into the sands on the upward or landward margin.

Spring pits seem possible of preservation in the geologic column, but it is not certain that such have been observed. Logan[233] described features

[228] Palmer, R. H., Sand holes of the strand, Jour. Geol., vol. 36, 1928, pp. 176–180.

[229] Deecke, W., Einige Beobachtungen am Sandstrande, Centralbl. f. Min., etc., 1906, pp. 721–727.

[230] Högborn, A. G., Zur Deutung der Scolithus-Sandstein und "Pipe-Rocks," Bull. Geol. Inst. Upsala, vol. 13, 1915, pp. 45–60.

[231] Andrée, K., Geologie des Meeresbodens, Bd. 2, 1920, pp. 187–191.

[232] Quirke, T. T., Spring pits; sedimentation phenomena, Jour. Geol., vol. 38, 1930, pp. 88–91.

[233] Logan, W. E., Geology of Canada, 1863, pp. 121–122.

in the Romaine dolomites of the Mingan Islands which he thought might have been caused by submarine springs, but the present writer's studies of the same features have indicated the impossibility of such origin.

SAND DOMES

Sand domes have been described by Reade.[234] While the structures have little or no geological application, they are sedimentary structures, and completeness requires attention to them. As described by Reade, they are small hollow domes or blisters 12 to 75 mm. in diameter and about 12 mm. high. The composing materials are sands which hold the arched position over the hollow due to being held together by enclosed water. In the examples described by Reade the sands overlay a blue clay, and the hollow space is ascribed to air that collects between the clay and the sand and lifts the latter. Sand domes have little chance of making a record in the geologic column.

MUD CRACKS

Mud cracks, also known as sun cracks and shrinkage cracks, bound polygons of irregular outlines. The directions and spacings of the cracks vary, being functions of the character of the materials, the rate of drying, the thickness, the presence of foreign matter, the degree of stratification, and the quantity of water held by the underlying material. There is a widespread impression that mud cracks are commonly six-sided, but polygons with six sides appear to be less common than those with three to five.

Mud cracks are developed wherever muddy sediments are exposed to the atmosphere for a considerable period of time, and their presence is thought to indicate that such conditions existed, but it is also possible for sediments to crack beneath water, although this does not seem to be common in nature.[235] Ice-crystal impressions somewhat resemble mud cracks, but the pattern is smaller.

Mud cracks occur most commonly in sediments composed of clay and silt, but they are present in sands which contain sufficient cohesive matter, and also develop in calcareous muds. The bottom surface of a stratum overlying one that is mud-cracked carries a counterpart of the mud-cracked surface, and these counterparts may occur in any sedimentary rock. Such counterparts are readily distinguished from originals by the absence of filled

[234] Reade, T. M., Miniature domes in sand, Geol. Mag., vol. 21, 1884, pp. 20–22.

[235] Twenhofel, W. H., Development of shrinkage cracks in sediments without exposure to the atmosphere, Abstract, Bull. Geol. Soc. Am., vol. 34, 1923, p. 64; Rept. Comm. Sedimentation, Nat. Research Council, 1925. Moore, E. S., Mud cracks open under water, Am. Jour. Sci., vol. 38, 1914, pp. 101–102.

cracks extending into the rock, as is the case in the originals. These characteristics are valuable criteria for determining tops and bottoms of beds.

The cracking of mud appears to start at places of greatest weakness; a buried stick or other object, the presence of a hole, the occurrence of sandy spots, or any substance weakening the cohesion leads to the development of cracking at that place. A hole or any object not uncommonly may be the source from which several cracks radiate. While not known, it is possible that pit and mound action may be responsible for initiation of radiate cracks. The various cracks develop in different directions, and their cross-

FIG. 96. MUD-CRACK POLYGONS OF WHICH MANY HAVE SIX SIDES

The possession of six sides is thought to be due to the homogeneity of the mud. The central parts of the polygons, according to Longwell, are slightly concave and there is some rounding at the edges due to falling off. The failure to turn up on the edges is thought to be due to the thickness of the mud layer. On a playa in the Las Vegas Quadrangle, Nevada. Photograph by Professor C. R. Longwell.

ing defines the polygons. The commonly assumed three cracks radiating from a point are probably exceptions in nature, though they may be seen to develop in very carefully prepared homogeneous muds. The general tendency appears to be for a crack to curve. A single crack may have a continuity of several feet, and the cracks first formed are usually longer than those which subsequently develop, and these latter ordinarily end abruptly at the older cracks. There is, however, wide variety.

The shapes of polygons vary within wide limits, those with three, four, five, and six sides being most commonly seen. There is no essential equal-

FIG. 97. DEVELOPMENT OF MUD CRACKS IN DIFFERENT PARTS OF THE SAME TANK

In the lower right-hand corner the polygons are arched upward in the middle. In the lower left-hand corner there is neither arching upward nor downward. Elsewhere there is turning upward on the edges. It will be noted that most cracks curve and that polygons are produced by intersection of cracks. The thicker the layer of mud, the wider the polygons, and where it is extremely thin, as in the upper right-hand corner, the cracks are close together. The pipe at the bottom of the photograph is one inch in diameter. Photograph by Diemer, University of Wisconsin.

ity to lengths of sides and to angles between sides. The commonly assumed six sides to mud-crack polygons with angles of 120° between the sides are fiction, but that such is true in some cases is shown by figure 96,[236] and perhaps is explainable as due to homogeneity of the muds. The variety in shape of mud-crack polygons may be seen in figure 97.[237] Cracks of a secondary or minor order may develop upon the polygons first formed. These are of less depth than the earlier cracks.

The spacing of mud cracks depends upon the character of the mud, the rate of drying, the thickness of the mud, the character of the water in which the mud was deposited, the nature of the material below, and the presence of foreign matter.

The width of the cracks probably is determined largely by the character of the muds and the spacing. Cracks are not uncommon with widths of 2 or more inches at the top. These are most common in thick-bedded muds. Studies made in the desert basin of northwestern Peru[238] showed an older system of cracks radial to the margin and a younger system parallel to the margin, the latter closely spaced at the margin and becoming further apart with approach to the center. The central area had great irregularity of crack trend. The crack polygons near the margin were four-sided, whereas in the middle most of them had five sides. It was thought that the controlling factors in spacing and trends of the cracks were shape of basin, thickness of mud, character of mud, and rate of drying.

Thick clay muds of homogeneous character give wider spacing than do muds that are in thin layers. Marly and limy muds give a narrow spacing. Sandy muds also tend to narrow spacing. "Rapid drying . . . seems to produce comparatively widely spaced mud cracks, while slow desiccation gives closely spaced mud cracks."[239] Muds which contain much foreign matter in the form of sticks, bits of straw, etc. give closer spacing than do the same muds in which such material is lacking. The mud cracks developed in water with a high degree of salinity are stated by Kindle to be very narrow, and highly saline muds show a slight lateral expansion which is accommodated "by the arching upwards of the median portions of the polygons,"[240] the arching in the cases observed on a marine beach in Florida being sufficient "to lift the centre of the polygon clear" of the underlying material.

[236] Longwell, C. R., Common types of desert mud cracks, Am. Jour. Sci., vol. 15, 1928, pp. 136–145.

[237] Kindle, E. M., Contrasted types of mud cracks, Trans. Roy. Soc. Canada, vol. 20, 1926, sect. iv, pp. 71–75.

[238] Suter, H., Beobachtungen über die Bildung von Trochnungsrissen in der Wüste von Nordwest-Peru, Centralbl. f. Min. etc., Abt. B. 1926, pp. 350–353.

[239] Kindle, E. M., Some factors affecting the development of mud cracks, Jour. Geol., vol. 25, 1917, p. 136.

[240] Kindle, E. M., op. cit., 1917, p. 142.

Mud-crack polygons may turn up or turn down at the edges, or do neither. This appears to depend upon the thickness of the mud layers and upon which portion of the cracked mud drys the more rapidly. Blocks composed of thin layers which dry more rapidly on top than elsewhere curve upward at the edges. If drying or extraction of water by underlying sands takes place more rapidly on the bottoms or the margins, the edges turn down, and in those cases where the rates of drying of the mud are the same on the top and bottom the top surfaces remain flat. All three types may be developed in the laboratory in the same tank with the same mud and water

FIG. 98. MUD-CRACK POLYGONS CURLING INTO ROLLS

The photograph shows that the rolls are most perfect where the mud is thinnest. (The cylinders, after being broken, roll on the edges of the fragments and ultimately a coin-shape is produced.) These cylinders rolling into deposits of sand form the Tongallen of the Germans. Meadow Valley Wash, Nevada. Photograph by Professor C. R. Longwell.

(fig. 97). It is probable that there are few conditions in nature which permit the bottom side to dry the faster. According to Kindle, "A high degree of salinity develops the formation of mud cracks in which the margins are inclined downward," and "the polygons formed in mud with the salinity of ordinary sea water warp neither upward nor downward at the margins, but retain a flat surface."[241] Kindle[242] further notes that mud cracks developed in air-slaked lime and fresh water are similar to mud cracks de-

[241] Kindle, E. M., op. cit., 1917, p. 139.

[242] Kindle, E. M., Separation of salt from saline water and mud, Bull. Geol. Soc. Am., vol. 29, 1918, pp. 479–488.

veloped in ordinary fresh-water mud. The same material with salt water gave surfaces with shallow V-shaped depressions of shallow depth, the surfaces between the depressions being flat. Mud-cracked clays from strongly saline solution show throughout the material "numerous very minute cavities and irregular pipe-like passages which are wanting in muds dried in fresh water." Mud-cracked polygons formed in fresh water ordinarily turn up at the edges if the surface mud can separate from the material below; if the latter is not possible, the edges remain flat and they may even turn down. Fine-grained muds in thin layers do the greatest turning up at the edges, this reaching extreme development in those instances where the mud curls into hollow cylinders to form the Tongallen of the Germans (fig. 98). Mud cracks in extremely saline muds may become filled with salts expelled by the drying polygons, thus giving a ridged rather than a cracked aspect to the surface.

Differential drying has been stated to be responsible for ribbon-shaped polygons, the cracks starting in the part first drying and thence extending into the other mud as it dries, the experiments having been carried out in small vessels.[243] Experiments conducted by the writer in large tanks have, however, only partly supported the generalization.

Temperature seems to be a factor in mud cracking. "Sediment deposited and kept under relatively high temperature conditions tends to crack freely in various directions while sediments kept under low temperature show no inclination to crack when desiccated."[244]

Mud-cracked polygons, on being wetted, begin slaking at the margins, which crack and slump away, leaving the middle of circular outline. The same results are produced by freezing and to some degree by the concentration of salts in the marginal portions. The slaking of muds on being wetted may be defined as wilting, and in some muds this requires considerable time, particularly when they carry a high content of lime carbonate and other salts and some colloids.

It has generally been assumed that when water covers mud-cracked surfaces the edges wilt so rapidly that no sediments are deposited beneath the upturned margins, but experiments have shown that where water-borne sediments are brought in large quantities to a mud-cracked surface, some may be deposited beneath the upturned edges of polygons of slow wilting. The deposition of sediments beneath the edges of mud-cracked polygons is best accomplished in arid regions by drifting sands, and an abundance of fossil mud cracks of this character is suggestive of an arid environment.

Mud cracks are far more abundant in non-marine than in marine sedi-

[243] Kindle, E. M., op. cit., 1917, p. 139.

[244] Kindle, E. M., Rept. Comm. Sedimentation, Nat. Research Council, 1924, p. 42.

ments. In modern marine and near-marine sediments they have a limited development on the littoral mud flats, particularly the upper portions. An extremely broad littoral of very gentle slope would have extensive areas exposed for every small variation of tide level, and mud cracking of considerable extent might obtain on beaches of suitable material. Such might have been the case during those times of the Paleozoic when the lands surrounding the interior seas were low and when swamp vegetation had not yet come into existence. The best example of supposed comparable conditions prevailing at the present time is over the Rann of Cutch about the mouth of the Indus River, where 8,000 square miles of area are bared for months at a time and at other times covered with marine water. Over this plain, mud cracking with marine associations occurs.

River flood plains and deltas, after subsiding of flood waters, become mud-cracked over areas which under some conditions may be coextensive with the areas flooded. This to some degree occurs annually over parts of the flood plains of the Mississippi, Missouri, Ohio, and other rivers. Conditions are particularly favorable if the climate is too dry to permit the development of much vegetation, as exemplified by the lower flood plain of the Euphrates-Tigris system, where the receding floods "leave a baked and burning wilderness of cracked mud behind."[245]

The finest development of mud cracks appears to obtain over the areas covered by the ephemeral lakes of arid regions. Each lake during its brief existence deposits a thin layer of mud, which after the water is gone becomes thoroughly cracked with the margins of the polygons strongly warped; but if the waters contain a great deal of salt, the growth of salt crystals in the polygons may reduce them to dust and fill the cracks with salt ridges. Longwell[246] has described three varieties of mud cracks found in the arid region of southern Nevada: (1) mud curls which are developed in fine muds in thin layers under conditions of rapid evaporation, (2) playa cracks with very symmetrical polygons, and (3) slope cracks of irregular trend with irregular outlines. The polygons of the second variety average about 3 inches in diameter, are composed of homogeneous materials, and are bounded by shallow cracks.

During long dry weather the deposits of deltas, flood plains, etc., may crack to depths of many feet, cracks with depths of several feet being known. Each time of cracking may lead to the formation of a crack in a different place, but the tendency appears to be to follow established lines. Every time of deposition fills all existing cracks, and the wetting causes wilting about the margins of the cracks. The result is greater or less destruction

[245] Peters, J. P., Am. Rev. of Rev., 1918, p. 404.
[246] Longwell, C. R., op. cit., 1928.

of bedding, and after deposits have passed through this experience for several years they may have undergone a thorough kneading and mixing, leading to total loss of stratification.

Cracks which are stated to be very similar to those made in the drying of muds develop on hard freezing. They have been noted by Spethmann[247] after a night temperature of −10°C. Hawkes[248] found by experiment that no effect was produced at temperatures of −2° to −3°C., but that fissures formed at −15°C. According to Leffingwell, the polygons have a tendency toward hexagonal form and resemble mud-crack polygons, but have larger dimensions, averaging about 16 feet in diameter.[249]

CLAY GALLS, CLAY PEBBLES, AND CLAY BOULDERS

Clay galls (Tongallen) develop from the cracking and curling up of thin layers of fine mud of great cohesion. The hollow cylinders may be rolled for considerable distances by wind and become incorporated in eolian or aqueous sediments. The cylinders then flatten and a thin lenticle of mud results. Cylinders may also become filled with sediments without much flattening and thus give rise to stem-like structures which may seem to be of organic origin. Structures thus interpreted have been described from sandstones of Scotland.[250]

Grabau expressed the opinion[251] that the presence of clay galls denoted subaerial origin; Richter[252] has shown, however, that they may develop between tides and are possible under water without any drying having taken place, the mechanics of origin being as follows. A sand flat in quiet water becomes covered with a thin sheet of mud which on retirement of the water attains considerable rigidity. Returning waters tear this sheet of mud from the underlying sands and break it into small plates with irregular outlines. These plates are easily transported. During transportation the angles may be reduced and deposition may take place in sandy or other sediments either seaward or shoreward from the place of origin.

Another very interesting method of clay-gall origin in which drying is

[247] Spethmann, H., Über Bodenbewegungen auf Island, Zeits. d. Gesell. für Erdkunde, 1912, p. 246.

[248] Hawkes, L., Frost action in surficial deposits, Iceland, Geol. Mag., vol. 61, 1924, pp. 509–513.

[249] Leffingwell, E. de K., Prof. Paper 109, U. S. Geol. Surv., 1919, pp. 205–206.

[250] Harkness, R., On the sandstones and breccias of the south of Scotland of an age subsequent to the Carboniferous period, Quart. Jour. Geol. Soc., vol. 12, 1856, pp. 264–265.

[251] Grabau, A. W., Principles of stratigraphy, 1913, pp. 564, 711.

[252] Richter, R., Flachseebeobachtungen zur Paläontologie und Geologie, XVI, Senckenbergiana, Bd. 8, Heft 5/6, 1926, pp. 312–315; see also Natur und Museum, Bd. 59, Heft 1, 1929, pp. 77–79, figs. 8–10.

only a minor factor has been described by Trusheim.[253] This was observed on the tidal flats of the North Sea, where thin muds covering the surface of the tidal plates contain more or less binding organic matter. Activity of micro-organisms forms gas in these muds, and much of this remains therein, leading to a porous texture and low density. Snails crawling about on this surface lead to the separation of the mud to some extent, so that with the incoming tide many flakes of mud float and may be carried far and wide over the tidal flat or out into open water, to be ultimately deposited with

FIG. 99. A CLAY BOULDER

This clay boulder, picked up on the shore of Lake Michigan, consists of clay in the inside and is studded with pebbles on the outside. The actual boulder is 16 cm. in its longest diameter, about 8 cm. in the medium diameter, and a little more than 4 cm. in the shortest diameter.

other sediments in strange association. The area of the flakes ranges from 1 to 10 square centimeters.

Thin lenticles of clay have been recorded from many sandstones into which entrance was obtained either as wind-transported cylinders or as wet plates. Criteria are lacking to distinguish the two methods of entrance. Beautiful examples of "Tongallen" are the lenticles of green clay in the Dresbach sandstones of western Wisconsin.

Most mud boulders and pebbles are formed from chunks of wet compacted

[253] Trusheim, F., Eigenartige Entstehung von Tongallen, Natur und Museum, Bd. 59, Heft 1, 1929, pp. 70–72, figs. 1–3.

mud loosed from a bank or cliff and rolled by a current on the bottom of a stream or other body of water. Pebbles, sand grains, pieces of vegetation, shells, and other substances may adhere to the mud as it rolls along (fig. 99). Adhering shells ordinarily appear to have the convex sides outward, seemingly because the sharp edges of shells make it easier for the concave side to adhere to the mud. Shells should not be far within a mud boulder, thus differing from concretions. A mud pebble or boulder may increase in diameter by adhesions of additional mud, thus acquiring a concentric structure, each band of which may be characterized by pebbles, sand grains, or other adhering objects. Cartwright[254] designates those boulders which are studded with small pebbles "pudding balls." Some mud boulders and pebbles form from dry mud which through undercutting falls into a stream in large or small chunks. These become wet and thus impervious on the exterior while remaining dry within, and through abrasion they may become round. Examples described by Haas[255] thus formed had diameters ranging to a foot. Boulders formed in this way from bentonite ultimately crack on the surface.

The operation of a dredge on Lake Wingra near Madison, Wisconsin, forced lake clay, sand, and water through a pipe about a half mile long. A great deal of the clay came out as small spheres studded with sand and small shells. Merrill[256] cites a similar occurrence arising from the operation of a dredge in the Potomac at Washington, D. C.

Mud balls, 2 inches in diameter, were seen in Bridger Canyon, Montana. Gardner[257] has described mud balls from the Rio Chaco of the San Juan Basin of New Mexico, and Patton[258] from the Red River of Oklahoma. The balls described by Gardner averaged $1\frac{1}{4}$ inches in diameter and occurred in great abundance. Some of them had nuclei of pebbles and possessed concentric lamination. The balls from the Red River of Oklahoma ranged up to 6 inches in diameter, and with them were cylinders up to a foot long. Both Gardner and Patton suggest that some concretions may have developed in this way. Fraas[259] and Walther[260] have noted the occurrence of mud pebbles on the shores of the Red Sea, and the former has described

[254] Cartwright, L. D., Sedimentation of the Pico formation, etc., Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, p. 254.

[255] Haas, W. H., Formation of clay balls, Jour. Geol., vol. 35, 1927, pp. 150–157.

[256] Merrill, G. P., Rocks, rock weathering and soils, 1906, p. 37.

[257] Gardner, J. H., Physical origin of certain concretions, Jour. Geol., vol. 16, 1908, pp. 452–458.

[258] Patton, L., In support of Gardner's theory of the origin of certain concretions, Jour. Geol., vol. 30, 1922, pp. 700–701.

[259] Fraas, O., Heuglin's geologische Untersuchungen in Ost Spitzbergen, Bd. 18, 1872, pp. 275–277.

[260] Walther, J., Einleitung in die Geologie, etc., pt. 3, 1894, p. 847.

them from the Jurassic of Spitzbergen. They have also been described from the North Sea by von Meyn (1876), from the Caspian by Tietze (1881), from Lake Constance by Schroeter and Kirchner (1902), and from the Baltic by Deecke. They have been discussed by Grabau,[261] and by Richter,[262] who has described them from the North Sea. Suter[263] has recorded them from the coast of Peru, where it is thought they are being deposited in sands.

The mud pebbles and boulders may become incorporated in sediments of any character, in which ordinarily they flatten as other sediments accumulate over them. They form under marine as well as continental conditions.

Closely related to mud boulders are those of peat, to which reference has already been made in connection with coarse clastics. These are not uncommon on some beaches, and they may possibly occur in the geologic column. Boulders of peat possess considerable coherence, have low specific gravity, and thus may be transported in waters of low competency.

COLUMNAR STRUCTURE

Columnar structure is given separate treatment, as it seems probable that the structure may arise in several different ways. Columnar structure in Silurian limestones of Quebec has been described by Kindle[264] and assigned to mud-cracking, the cracks extending to depths of 10 to 24 inches and later becoming filled with sediments more argillaceous than those in which the cracks developed.

Branson and Tarr[265] have described columnar structure normal to bedding planes in the Gallatin limestone of Wyoming, most of the columns ranging from 4 to 6 feet long, but with a few of less length. Diameters range from 3 to 12 inches. The columns are sub-angular in cross section and have three to eight striated and fluted sides, the striations, as a rule, being parallel to the axes of the columns. Some of the columns contain rude cones at ir-

[261] Grabau, A. W., Principles of stratigraphy, 1913, p. 711.

[262] Richter, R., Flachseebeobachtungen zur Paläontologie und Geologie, VI, Ton als Geröll im gleichzeitigen Sediment, Senckenbergiana, Bd. 4, Heft 5, 1922, pp. 137–141; XI, Schlickgerölle, auf dem Meeresgrund entstehend, Ibid., Bd. 6, Heft 3/4, 1924, pp. 163–165; XVI, Die Entstehung von Tongeröllen und Tongallen unter Wasser, Ibid., Bd. 8, Heft 5/6, 1926, pp. 305–312. Richter gives a considerable review of the literature, and the uncited references given above are on his authority.

[263] Suter, H., Eine Beobachtung über die Bildung von Geröllen aus Tonen, Mitth. Schweiz. Min. u. Petrogr. Bd. 6, 1926, pp. 202–203.

[264] Kindle, E. M., Columnar structure in limestone, Mus. Bull. No. 2, Geol. Ser. No. 14, Geol. Surv., Canada, 1914, pp. 35–39.

[265] Branson, E. B., and Tarr, W. A., New types of columnar and buttress structures, Bull. Geol. Soc. Am., vol. 39, 1928, pp. 1149–1156.

regular intervals, the cones being from 2 to 4 inches in diameter at the base and up to $1\frac{1}{2}$ inches high. Their axes are parallel to the sides of the containing column. These are not true cone-in-cone and are considered exceptional developments of stylolitic structure. The columns also contain stylolitic seams which are roughly parallel to bedding planes and normal to the side of a column. Branson and Tarr consider each column "an unusually large development of a stylolitic column which extends from the top to the bottom of the bed."

Columnar structures have been described in the Ordovician limestone forming Silliman's Fossil Mount, Frobisher Bay, Baffin Land, where they are considered to have developed from tensional forces developed in the uplift of the area.[266] If such is the origin, these are not sedimentary structures. Salisbury[267] has described columnar structure in clay and referred the origin to concretionary processes.

CONCRETIONS[268]

BY W. A. TARR AND W. H. TWENHOFEL

A concretion is defined as an aggregate, in sediments, of inorganic matter in nodular, discoidal, rhizoid, cylindrical, or other form. A nucleus of some sort is frequently present and the structure is very commonly concentric, although neither feature is essential. Oolites and pisolites are the most abundant concretionary bodies, but as these have a different significance from other concretions, they are separately considered. Concretions are common in most sedimentary rocks and may be found in those of any age from the oldest to those now forming.

Much diversity of opinion exists respecting the origin of concretions, and it is probable that they develop as a consequence of combinations of several different groups of variable factors. As an asset in geologic work, they are given little standing, generally being regarded as little more than curiosities.

Composition

A concretion is commonly composed of a single material, but one or more other substances are apt to be present as impurities. The most common composing materials are calcite, silica, hematite, limonite, siderite, pyrite and marcasite, gypsum, barite, aragonite, witherite, manganese oxide,

[266] Roy, S. K., Columnar structure in limestone, Science, vol. 70, 1929, pp. 140–141.

[267] Salisbury, R. D., Columnar structure in subaqueous clay, Science, vol. 5, 1885, p. 287.

[268] Kindle, E. M., Range and distribution of certain types of Canadian Pleistocene concretions, Bull. Geol. Soc. Am., vol. 34, 1923, pp. 609–646. This paper contains an extensive bibliography on concretions.

calcium phosphate, fluorite, and bauxite, the six first named being the most common.

Calcite is the chief material in claystones and in the calcareous concretions so common in shales and sandstones. The loess concretions are very largely calcite. Concretions composed of calcite have been dredged from the sea bottom of Auckland Harbor, New Zealand, and are also now forming in the soils of many arid regions. Aragonite is not commonly known in concretions, but a recent paper[269] describes concretions composed of this mineral which occur in a single locality in the Tertiary of the Kettleman Hills region of California. They are found in a zone of fine silt a few inches thick; this zone locally resting upon a bed of gypsum. The concretions are less than 6 inches in diameter, have radial structure, and some have a small central cavity. The surfaces are like those of marlyte balls.

Siliceous concretions usually are nearly pure silica, most commonly in the form of chert and flint, though some are chalcedony. Some concretions in sandstone consist of quartz sands cemented by silica or carbonate; such are the sand concretions in the Cambrian sandstones of the upper Mississippi Valley, those known as "Acrespire" in the Millstone Grit of Yorkshire,[270] and those of many other horizons. The cement in the concretions of the regions just named is carbonate.

Hematite and limonite concretions are the most common ones in sandstones, the concretions usually being composed of quartz sands cemented by hydrous or anhydrous iron oxide. In limestones, the entire concretion may consist of hematite or other oxide of iron. The "buck shot" concretions of soils, and the pseudomorphs after concretions of pyrite, marcasite, and siderite, are usually nearly pure iron oxide. Iron-oxide concretions have been collected in modern Swedish and American lakes,[271] and are forming in some soils, particularly laterites.

Siderite is often an important constituent of clay ironstones, and many concretions in clay, the exteriors of which appear to be composed of iron oxide, have siderite on the interior, the carbonate having altered to the oxide on the exterior.

Pyrite and marcasite concretions are of widespread occurrence. They are found in shale, limestone, coal, and sandstone, and are particularly common in dark shales of marine origin.

[269] Reed, R. D., Aragonite concretions from the Kettleman Hills, California, Jour. Geol., vol. 34, 1926, pp. 829–833.

[270] Stocks, H. B., On a concretion called Acrespire, Proc. Yorkshire Geol. and Polyt. Soc., vol. 9, 1887, pp. 149–150.

[271] Shaler, N. S., Tenth Ann. Rept. U. S. Geol. Surv., pt. i, 1890, p. 305; Harder, E. C., Prof. Paper 113, U. S. Geol. Surv., 1919, p. 53; Beck, R., The nature of ore deposits, 1909, pp. 98–101.

Gypsum concretions are very common in some of the shales and sandstones of the Red Beds. Very commonly, however, the gypsum is in the form of selenite crystals or crystalline aggregates.

Barite occurs as concretions (known under such names as "petrified roses" and "barite dollars") in the Red Beds of Oklahoma and Texas, the Elgin Triassic of England, and elsewhere. Nodules composed largely of barium sulphate occur on the sea bottom, and small ones have been taken from an oil well in the Saratoga oil field of Texas. Concretions of witherite are rare, those known consisting of bodies of sand cemented with this material. Manganese oxide in the form of wad or psilomelane forms concretions in many sedimentary rocks, and cements other materials on the present sea bottom to form nodular bodies. Calcium phosphate also forms nodular bodies like those of manganese on the present sea bottom, and it is found in the form of small nodules in marine deposits. Bauxite is very commonly aggregated in pisolitic and concretionary form, as in the bauxite deposits of Arkansas. Fluorite concretions are rare, occurring as small aggregates and isolated individuals in the Triassic sandstones of England.

Shape

Shapes of concretions are so extremely variable that it is difficult to formulate a classification. For purposes of convenience, they may be grouped as (1) spherical, including discoidal and ellipsoidal; (2) cylindrical; and (3) nodular or irregular.

1. Calcite concretions of spherical or nearly spherical shapes occur at Kettle Point, Ontario. Nearly spherical concretions are present in the Virgelle sandstone member of the Eagle formation northwest of Lewistown, Montana, and such are extremely abundant in some of the Cambrian sandstones of the upper Mississippi Valley. Spherical concretions of pyrite or marcasite are locally common in the Morrison shales south of Billings, Montana, some being nearly 2 inches in diameter. The ellipsoidal and discoidal forms of concretions may be original, or both may have developed through flattening of spherical concretions. Excellent examples of discoidal concretions are those in the Champlain clays of the Connecticut River Valley, and many of these have shapes resembling real or fancied organisms. Chert and flint concretions frequently have ellipsoidal shapes.

2. Cylindrical shapes are not uncommon among pyrite, marcasite, and iron-oxide concretions; and calcite concretions, particularly those of loess, not infrequently have this shape. Common lengths do not exceed a foot, and diameters are an inch or more, but log-like concretions in the "Laramie" of South Dakota are said to attain lengths exceeding 100 feet.[272]

[272] Todd, J. E., Loglike concretions and fossil shores, Am. Geol., vol. 17, 1896, pp. 347–349.

3. Concretions of irregular shapes may develop through the lateral union of separate concretions, or they may assume these shapes as original growths. Extremely fanciful forms have developed, particularly among concretions composed of silica and iron oxide, some of which have been identified as roots,[273] animals, birds, household articles, or parts of the human body. An odd variety of concretion is that in the form of a ring found in glacial clays of Iceland, and one of this form has been collected in England. These are less than 4 inches in diameter, and are assumed to have formed around pebbles.[274]

Size

The largest concretions are thought to form in sandstone. The Wilcox formation of eastern Texas and western Louisiana is said to contain sandstone concretions 20 to 30 feet long, and some of the log-like concretions of the Laramie, as above noted, reach a length of 100 feet.[275] Concretions up to 12 feet in diameter occur in the Dakota sandstone of Kansas. Newberry described concretions 10 feet in diameter in the Devonian of Ohio, and many concretions as large as 8 feet in diameter occur in the Virgelle sandstone of central Montana. The Cretaceous Carlile shales in the northern Black Hills contain spherical concretions 5 to 7 feet in diameter, and discoidal concretions 12 feet wide and 1½ feet thick.

Chert and flint concretions rarely attain large size, about 5 feet being a fair maximum, although the large chert bodies may merely be unions of smaller ones. Claystones, as those found in the Champlain clays of the Connecticut Valley, rarely exceed a few inches in length, the largest one found by Sheldon being 22 inches long, and it may have been due to the coalescence of smaller concretions. Most concretions obtained from the sea bottom are only a fraction of an inch in diameter. A few are larger.

Theoretically, epigenetic concretions in sandstone might attain almost any dimensions, as the limiting factors are the quantity of cementing material available and the thickness and extent of the sandstone. The sizes of concretions in shale are more limited, as growth of syngenetic concretions ceases after burial, and epigenetic concretions in shale have their growths limited by the virtual impossibility of replacement or displacement of the enclosing shale. The size of concretions replacing limestone is limited chiefly by the amount of the replacing material available.

[273] Kindle, E. M., A note on rhizoconcretions, Jour. Geol., vol. 33, 1925, pp. 744–746.

[274] Hawkes, L., A note on calcareous "rings" formed in glacial clays, Proc. Geologists' Assoc., vol. 35, 1924, pp. 260–262.

[275] Todd, J. E., Concretions and their geological effects, Bull. Geol. Soc. Am., vol. 14, 1903, pp. 353–368.

Surface features

Some concretions are readily separable from the enclosing rock, and these usually have relatively smooth surfaces; most surfaces are more or less rough and irregular. The surfaces of some concretions are covered with fossils, and some have slickensided surfaces on the upper side. It is not known whether the latter are due to the surrounding beds slipping down around the concretions during consolidation or to the upward growth of concretions.

Internal structure

Concretions may have concentrically laminated or radial structure or may be amorphous. The calcite concretions in the Devonian at Kettle Point,[276] Ontario, and in Michigan[277] have both radial and concentric structure. Many pyrite and marcasite concretions are radial in structure, and this type may also be found in gypsum and iron-oxide concretions. Most concretions show concentric structure to some degree, the formation of which has been accomplished through addition of successive layers to the outside. Each layer may have a radiate structure.

Concretions may have uniform texture and color throughout, but usually there are variations in different parts, giving rise to color banding and mottling. Mottling is best seen in chert concretions, the differences in color being due to varying quantities of carbonaceous material, iron oxides, or other coloring agents. Siderite concretions show a mottling which is chiefly due to secondary changes of oxidation and hydration.

Lines of horizontal stratification extend through some concretions. These are thought to represent bedding planes: they may or may not correspond to those of the enclosing rock. Some sandstone concretions have this stratification in a marked degree. It is usually less obvious in claystones and calcareous and chert concretions, although it may appear sharply after weathering.

Septaria are a form of concretion that possesses filled or open cracks or veins, the cracks seemingly widening toward the interior.[278] Septaria are usually composed of calcite, and this is the most common substance found filling the cracks or veins. Veins are commonly less than 2 inches in width, and the composing minerals usually are oriented perpendicular to the walls. In veins not completely filled, the minerals may terminate in crystal faces.

[276] Daly, R. A., The calcareous concretions of Kettle Point, Lambton Co., Ont., Jour. Geol., vol. 8, 1900, pp. 135–150.

[277] Rominger, C. L., Black shales of Michigan, Geol. Surv., Mich., vol. 3, 1873–1876, pp. 63–67.

[278] Geikie, J., Structural and field geology, 1920, p. 122.

Beautiful crystals of barite and selenite have been obtained from septaria in the Pierre shale of Nebraska,[279] and crystals of marcasite, pyrite, arsenopyrite, millerite, galena, sphalerite, and chalcopyrite from septaria of other localities.[280] Septaria resemble and are frequently mistaken for fossil turtles. Cone-in-cone not infrequently is associated with septaria as well as other concretions, and the septaria not uncommonly possess slickensided surfaces.

The cracks of septaria have been considered by many students as arising from the shrinking and cracking of the material of the interior;[281] Todd[282] suggested that the exterior expanded through the addition of material and thus pulled the interior apart; and Davies[283] advanced the view that the interior expanded to produce the cracks. The views of Richardson with slight modifications, or rather, additions, seem the best explanation proposed to date. To form a septarium, a concretion with a colloidal central area is postulated. This ultimately becomes a crystalline solid, the process resulting in shrinkage accompanied by cracking. Shrinkage may also be postulated to result from expulsion of water from the saturated central area. At some later date minerals are deposited in the cracks, the walls of which are pushed farther apart by such growth and the cracks are extended to the exterior, the process being like that by which geodes develop within fossils.[284] Under such conditions the cracks or veins become widest in the exterior part of the structure. The common occurrence of septaria in clays is explained on the basis that the clays are composed in large part of colloids and these are suited for forming the central parts of septaria.

Septaria are widely distributed throughout the world in Paleozoic and Mesozoic strata. They are particularly abundant in the Cretaceous formations in Nebraska, Wyoming, the Dakotas, and Montana; the Devonian in New York, Pennsylvania, and Ohio; and the Pennsylvanian of the Mississippi Valley region.

It may sometimes happen that a septarium is acted upon by a solution, resulting in removal of everything except the fillings of the cracks, thus giving a skeleton structure of peculiar form. In the early Quaternary alluvial deposits of Brazos County, Texas, are structures composed of quartz

[279] Barbour, C. A., Observations on the concretions of the Pierre shale, Publ. 7, Nebraska Acad. Sci., 1901, pp. 36–38.

[280] Lindgren, W., Mineral deposits, 1913, p. 237.

[281] Richardson, W. A., On the origin of septarian structure, Min. Mag., vol. 56, 1919, pp. 327–338.

[282] Todd, J. E., op. cit., 1903, p. 359; Geol. Mag., vol. 50, 1913, pp. 361–364.

[283] Davies, A. M., The origin of septarian structure, Geol. Mag., vol. 50, 1913, pp. 99–101.

[284] Bassler, R. S., The formation of geodes, etc., Proc. U. S. Nat. Mus., vol. 35, 1908, pp. 133–154, pls. 18–20.

which resemble such septarium skeletons and at first were believed to be such. These have been designated *melikaria*,[285] and they are stated to have formed in place through deposition of silica from rising waters in the bottoms of deep desiccation cracks. Dimensions are as large as 18 by 8 by 4.5 inches. Similar structures are present in some of the gypsum-bearing beds of the Permian of Oklahoma, but whether the origin is the same is not known.

A structure allied to the concretion is the geode, the term being applied to a partly filled hole in a rock which has weathered out from its surroundings and also to a cavity lined with crystals. A geode may form through the deposition of material from solution upon the walls of a hole, but a very common method of origin is by the deposition of material from solution, chiefly calcite and quartz, along structural and fracture lines of the shells of organisms, with the result that the volume enclosed within the shell progressively increases in diameter. The secondary enlargement is not essential, however, if the interior part of the shell is empty as deposition may occur within this cavity. This type of geode is common in the Mississippian strata of Missouri. Every stage in the growth of geodes through secondary enlargement from crinoids, brachiopods, gastropods, and other shells may be seen in Mississippian strata on the west side of the Cincinnati Arch in Indiana and Kentucky.[286]

Some concretions are composed of concentric laminæ differing in composition, and through solution the more soluble of these laminæ may be removed and thus a central part may become detached, forming a *rattlestone* or Klapperstein. In a similar manner, parts of the interior of septaria may be released. Sandstone concretions of iron oxide frequently have a central core of uncemented sand which rattles on shaking. This sand is frequently pure white, possibly the original color, or it may have been leached of an original iron content.

Nuclei

The majority of concretions do not contain nuclei, and it does not seem essential that there should be one. Any saturated or supersaturated solution by a change in physical or chemical conditions, or by reaction, may precipitate some of the substances in solution, and these first particles would serve as nuclei around which aggregation might take place. It would be impossible to locate this originating center. It is also possible, of course, that a nucleus originally present may have disappeared.

Nuclei that have been found consist of inorganic materials, chiefly detrital

[285] Burt, F. A., Melikaria: vein complexes resembling septaria veins in form, Jour. Geol., vol. 36, 1928, pp. 539–544.

[286] Bassler, R. S., op. cit.

grains; and of organic materials, such as shells and parts of shells, coprolites, complete organisms (as insects and fish), and leaves and other parts of plants.

Nuclei or organic matter not uncommonly are extremely well preserved, as exemplified by the leaves, insects, and other fossils in the famous Mazon Creek locality of Illinois and the fish skulls with perfect preservation of the cranial cavity in the Douglas stage of the Pennsylvanian near Lawrence, Kansas. The preservation of the organic matter is usually much better in the concretions than it is in the enclosing rocks, a fact having important bearing on the time of origin of such concretions.

Modes of Occurrence

The modes of occurrence of concretions are important and essential to an understanding of their origin. Occurrences need to be studied as to (1) the nature of the enclosing rock and the concretions, and (2) the relationships of concretions to the enclosing rocks, that is, whether the concretions are within beds or between beds, and what the orientations are to the bedding planes.

NATURE OF ENCLOSING ROCK. Concretions occur in all or nearly all varieties of sedimentary rock, evaporation products being the only possible exception and there seem to be no good reasons why they should not also be there.

Concretions in clay and shale, in their approximate order of abundance, are composed of calcite or calcite mixed with clay, pyrite or marcasite, siderite, calcium phosphate, gypsum, and barite. The concretions in black shales are most often composed of pyrite or marcasite, and those of gray shales containing considerable organic matter, as those of the Coal Measures, seem to be commonly of siderite or sideritic. Concretions in sandstone consist mostly of sand grains cemented by iron oxide, calcite, or silica, the three cements in their approximate order of abundance. Less commonly, the cement is barite or the manganese oxides. The most common concretions in limestones are composed of silica in the form of flint or chert, and concretions in coal are chiefly pyrite and marcasite.

RELATIONS TO ENCLOSING ROCK. Concretions in general are distributed along bedding planes or lie within beds.

Concretions along bedding planes usually lie in shallow depressions in the underlying bed. Stratification planes in the overlying bed may curve upward over the concretion, or terminate against it abruptly or with a slight upward curve. Some stratification planes pass through concretions without interruption. Rarely, stratification planes curve equally over and under a concretion.

Concretions within beds are common, with the exception of those of flint and chert, but are less so than along bedding planes. They may occur irregularly within a bed, but usually they are along a definite horizon. All variety of distribution may be seen in many quarries, as those in the Oneota dolomite near Madison, Wisconsin, the Mississippian limestone at Branden-

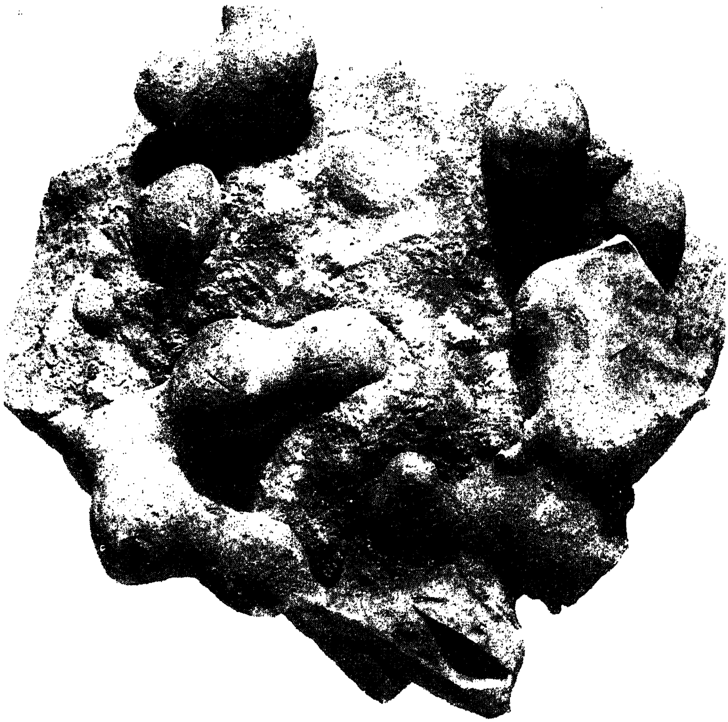


FIG. 100. CHERT NODULES IN THE ST. LOUIS LIMESTONE

The upper bedding plane is shown. The nodules in the St. Louis limestone, Mississippian, in the region where this slab was collected tend to be spherical or ellipsoidal. Specimen collected in the old lithographic stone quarry, Brandenburg, Meade County, Kentucky. About one half natural size. Photograph by Diemer, University of Wisconsin.

burg, Kentucky, the Foraker limestone of Cowley County, Kansas, the Burlington limestone in Missouri, and the chalk cliffs of the south coast of England. Some concretions cross stratification planes.

The most common orientation of concretions is with the longest axes parallel to stratification planes, though this is not always the case (fig. 100).

MODE OF OCCURRENCE AFFECTED BY KIND OF ROCK. Differences in

stratification in different rocks cause one or another of the modes of occurrence to be associated with certain rocks. The rather abundant occurrence of stratification planes in shales causes most concretions therein to be associated with such planes, though concretions also occur wholly within beds of shales and even extend across stratification planes whereupon they present the appearance of superimposed disks or lenses. Concretions within beds are more possible in the thicker bedded limestones, but even so, in some localities they seem more abundant along stratification planes. Concretions in sandstones usually represent bodies of sandstones locally cemented since deposition. The bedding planes of sandstones are generally no more important in permitting the passage of cement-carrying solutions than are other parts of the rock, and there is thus a lesser tendency for concretions to be confined to bedding planes. This condition makes it possible for concretions in sandstone to become very large, and for stratification planes in the sandstones to pass through them without interruption. Concretions in coal are commonly along stratification planes, where they are often associated with clay partings. Concretions of pyrite are not of uncommon occurrence with a coal bed.

Geologic Distribution

Concretions occur in the rocks of all systems. Chert concretions are common in Cambrian, Ordovician, and Mississippian rocks, and flint concretions in the chalks of the Cretaceous. Calcareous concretions are abundant in the eastern Devonian, the Cretaceous east of the Rocky Mountains, and some Pleistocene deposits. Siliceous concretions appear to be most abundant in Paleozoic rocks, and calcareous in the later systems. Whether this time distribution has any important significance is not known.

Classification

Classification of concretions may be based upon origin, form, composition, or time relation to the enclosing rock. Neither form nor composition offers a satisfactory basis, and a classification based on origin and time relations to enclosing rock must necessarily be tentative as existing knowledge on these scores is very incomplete. This work considers a classification based on time relations to the enclosing rock as most satisfactory.

Todd's[287] classification based on method of growth proposed four divisions:

A. Accretions, or growth outward.
B. Intercretions, concretions with cracks on the inside more or less filled with minerals.

[287] Todd, J. E., Concretions and their geological effects, Bull. Geol. Soc. Am., vol. 14, 1903, pp. 353–368.

C. Excretions, or growth inward. (Todd rightly questions placing these among concretions.)
D. Incretions, or growth inward, as around root cavities. (These are common in loess.)

Todd considers the last two terms questionable. As there is limited information relating to the method of growth of concretions, its use as a basis for classification is not satisfactory.

Merrill's[288] classification based on time relationships to the enclosing rock places concretions in two groups:

A. Primary concretions, formed contemporaneously with the enclosing rock.
B. Secondary concretions, due to segregating influences acting subsequently to the formation of the enclosing rock.

Except for differences of statement, this classification is also that of Sorby[289] and Grabau.[290]

Richardson's[291] classification, also based on time relationships, gives three groups:

A. Contemporaneous; formed at the same time as the surrounding rock.
B. Penecontemporaneous; segregated close to the surface of recently deposited sediments.
C. Subsequent; formed after the rock was consolidated.

A two-fold grouping with respect to time relationships is favored, using *syngenetic* rather than primary or contemporaneous, and *epigenetic* rather than secondary or subsequent. The use of penecontemporaneous is not favored. Syngenetic is here used to include concretions formed at the same time the surrounding sediments were being deposited, and epigenetic to include those concretions formed after deposition of the enclosing rock. It naturally follows that there is no sharp division, and concretions no doubt exist of which the central portions are syngenetic and the exterior portions epigenetic because of additions after burial beneath sediments. Syngenetic growth would stop as a concretion becomes buried, but epigenetic growth might then begin.

Origin

Much has been written relating to the origin of concretions, and there is considerable difference of opinion. The chief difficulty seems to have been

288 Merrill, G. P., Rocks, rock weathering and soils, 1906, pp. 35–37.
289 Sorby, H. C., Concretions, Quart. Jour. Geol. Soc., London, vol. 64, 1908, pp. 215–220.
290 Grabau, A. W., Principles of stratigraphy, 1913, pp. 718–726, 763.
291 Richardson, W. A., The relative age of concretions, Geol. Mag., vol. 58, 1921, pp. 114–124.

the assumption that a single method of origin was necessary. It seems probable that the various structures known as "concretions" may originate in three ways, as follows:

1. Physical, as rounding and enlargement of mud balls.
2. Organic, as algal growths.
3. Chemical, aggregated through chemical action, either
   a. As precipitates while enclosing rock was being deposited, or
   b. As aggregates deposited within the enclosing rock after its deposition.

CONCRETIONS OF PHYSICAL ORIGIN. The only structures developing in a purely physical way which might be identified as concretions are clay pebbles and boulders enlarged by mechanical accretion. Bourne[292] believed that certain little pellets exposed by a slide on the Connecticut River had developed in this way; Merrill[293] gives this as a method of the origin of some concretions; and Gardner[294] has suggested that many claystones may be of this origin. It is not thought best, however, that such structures as clay pebbles and boulders should be included among concretions, and, where it can be shown that their origin was mechanical, they should not be so classified.

CONCRETIONS OF ORGANIC ORIGIN. Many structures of concretionary appearance are of organic origin. Such are exemplified by those of some algæ, as *Cryptozoon*, and hydroid corals, as *Clathrodictyon*. Roddy[295] has stated that calcareous "concretions" 8 to 10 inches in diameter may be formed by plant agencies in streams rich in dissolved calcium carbonate, and Clarke[296] has described similar structures in Canandaigua Lake, New York. Mawson[297] shows their occurrence, by thousands, in depressions between dunes in southwestern Australia; Stow[298] has noted their presence in streams near Lexington, Virginia; and there are many other descriptions. The writers do not believe in designating these algal structures concretions, though they are unable to give the criteria to differentiate algal bodies from concentric concretions if the organic structure of the algal body has been destroyed by crystallization.

[292] Bourne, C. E., History of Wells and Kennebunk, 1875.

[293] Merrill, G. P., Rocks, rock weathering and soils, 1906, p. 33.

[294] Gardner, J. H., The physical origin of certain concretions, Jour. Geol., vol. 16, 1908, pp. 452–458.

[295] Roddy, H. J., Concretions in streams formed by the agency of blue-green algæ and related plants, Proc. Am. Philos. Soc., vol. 54, 1915, pp. 246–258.

[296] Clarke, J. M., The water biscuits of Squaw Island, Canandaigua Lake, New York, Bull. 39, New York State Museum, vol. 8, 1900, pp. 195–198.

[297] Mawson, D., Some South Australian algal limestones in process of formation, Quart. Jour. Geol. Soc., vol. 85, 1929, pp. 613–623.

[298] Stow, M. H., Calcareous concretions in streams near Lexington, Virginia, Am. Jour. Sci., vol. 20, 1930, pp. 214–216.

CONCRETIONS OF CHEMICAL ORIGIN. The majority of concretions probably owe the aggregation of their composing materials to chemical processes, time relationships being either syngenetic or epigenetic.

Syngenetic concretions. Syngenetic origin involves precipitation of material from solution, or the coagulation of a colloidal suspension.

Prestwich was the first to advance the theory that chert concretions are of syngenetic origin, considering the precipitating agents to be either siliceous sponge spicules or decaying organic matter. Tarr[299] advocated the syngenetic origin of the chert concretions in the Burlington limestone, and a like origin for concretions in Pennsylvanian shales in Missouri and Cretaceous shales in South Dakota, Montana, and Saskatchewan, and he concludes that "Most concretions which occur in shales are probably of syngenetic origin." Rubey[300] is in accord with Tarr with respect to the calcareous concretions in the Cretaceous about the Black Hills. Sargent[301] advocated a syngenetic origin for the Carboniferous cherts of Derbyshire, England, considering the silica to have been precipitated along with the associated sediments. Brydone[302] holds that the hollow flints of the chalk beds are most likely of contemporaneous or penecontemporaneous origin and that "on the whole a penecontemporaneous origin for row and tabular flints seems to present the minimum of conflict with facts." Studies made by Brinkmann of Jurassic ammonites collected in England from concretions in dark shales show that fossils in the concretions are undeformed, whereas any part of a shell projecting from a concretion into the surrounding shale is mashed flat and distorted, seemingly proving the syngenetic origin of the concretions.[303]

The idea that concretions of calcium carbonate might be of syngenetic origin was advanced many years ago by Hall[304] in describing a concretionary layer of the Tully limestone. He stated that "the layer seems to be due to the fact of there not being enough of the calcareous material to form a stratum, when it was collecting on the bottom, and so it collected into spheres." Tarr independently reached the same conclusion, that calcareous

[299] Tarr, W. A., Origin of the chert in the Burlington limestone, Am. Jour. Sci., vol. 44, 1917, pp. 409–452; Syngenetic origin of concretions in shale, Bull. Geol. Soc. Am., vol. 32, 1921, pp. 373–384; Science, vol. 51, 1920, p. 520.

[300] Rubey, W. W., Prof. Paper 165A, U. S. Geol. Surv., 1930, p. 11.

[301] Sargent, H. C., The Lower Carboniferous cherts of Derbyshire, Geol. Mag., vol. 58, 1921, pp. 265–278.

[302] Brydone, R. M., The origin of flint, Geol. Mag., vol. 57, 1920, pp. 401–404.

[303] Brinkmann, R., Statistisch-biostratigraphische Untersuchungen an mittel-jurassischen Ammoniten über Artbegriff und Stammesentwicklung, Abh. d. Gesells. d. Wiss. zu Göttingen, Bd. 13, 1929, pp. 249; Reviewed Neues Jahrb., 1929, p. 400.

[304] Hall, J., Geology of New York, pt. iv, 1843, p. 192.

concretions may represent insufficient material to make a bed, and Lucas[305] explained some nodular clay ironstones as having formed in depressions on the floors of lagoons.

Calcareous concretions (coal balls or "bullions") found in the coal beds of the Lower Coal Measures in England are regarded by Stopes and Watson[306] as due to material introduced into the coal from the sea water immediately above, after the coal had been laid down but before it had become consolidated, thus assigning a syngenetic origin to the coal balls. Stocks[307] seems to have held a similar view.

The calcareous concretions dredged from Auckland Harbor, New Zealand,[308] however, confirm the correctness of the syngenetic view, as they show that concretions may grow during the accumulation of the sediments. The concretions contain about 70 per cent calcium carbonate, and are less than 6 inches in diameter. Shells, small crabs, and other matter serve as nuclei. A few of the larger concretions have irregular drusy cavities as large as 0.5 inch in diameter. These are not due to solution. Shells lacking a horny epidermis do not serve as nuclei, whence it was assumed that decomposition of epidermal matter initiates the deposition of carbonate, resulting in the concretions. The concretions formed on the sea bottom at depths of 28 to 35 feet.

The concretions of the famous Pennsylvanian locality at Mazon Creek, Illinois, which have such wonderfully preserved enclosed fossils, seem to be syngenetic. The iron concretions of Swedish, Canadian, and other lakes are certainly syngenetic, and of like origin are the manganese and phosphatic nodules of the present sea bottom.

The pyrite concretions of the dark Pennsylvanian shales of north-central Missouri have been shown by Mathias[309] to be of syngenetic origin and all pyrite concretions (and marcasite as well) seem best interpreted as of this origin.

Epigenetic concretions. Epigenetic concretions are very abundant in sandstone and to a less degree in shale and limestone. They may be either displacive or replacive. To form an aggregate of any material in a rock, it

[305] Lucas, J., On the origin of clay-ironstone, Quart. Jour. Geol. Soc., vol. 29, 1873, pp. 363–369.

[306] Stopes, M. C., and Watson, D. M. S., On the present distribution and origin of the calcareous concretions in coal-seams, known as "coal-balls," Philos. Trans. Roy. Soc., ser. B., vol. 200, 1909, pp. 167–218.

[307] Stocks, H. B., On certain concretions from the lower Coal Measures and the fossil plants which they contain, Proc. Roy. Soc. Edinburgh, vol. 20, 1893, pp. 70–75.

[308] Bartrum, J. A., Concretions in the recent sediments of the Auckland Harbor, New Zealand, Trans. New Zealand Inst., vol. 49, 1916, pp. 425–428.

[309] Mathias, H. E., Syngenetic origin of pyrite concretions in the Pennsylvanian shales of north-central Missouri, Jour. Geol., vol. 36, 1928, pp. 440–450.

is essential that solutions should be able to move through the rock in order to obtain the material for the concretion. Most sandstones readily permit migration of solutions. This is shown by the usual spherical form of concretions in sandstones, the solutions being able to bring material from all sides. The porosity of shales and limestones is low, and free movement of solutions should be mainly confined to divisional openings, to which, therefore, epigenetic concretions should be largely limited. However, the two factors of time and materials initiating precipitation must be considered, and where these materials are within a bed it seems probable that diffusion, however slow, if given sufficient time may develop epigenetic concretions in any sedimentary rock. This is thought to be proved by the development of lime concretions in clay soils of dry regions. Sheldon[310] states that the Connecticut Valley concretions resulted from the aggregation of small quantities of calcium in the clays, and that circulating ground waters acted as the collecting and transporting agent. This calcium carbonate cemented into the concretions most of the materials of the clays at the places where the concretions formed. Nichols[311] pointed out the difficulty of explaining why the same solution should dissolve at one point and deposit in another, and suggested that much of the dissolved calcium carbonate was originally in the form of aragonite, a suggestion of doubtful value and certainly applicable with difficulty to such concretions as those in the post-glacial clays of the Connecticut River Valley. The difficulty of explanation is a real one, but differential solution is unquestionable and the highly variable character of the materials composing clays, as well as the extreme variability of circulation, permits the assumption that many factors might favor differential deposition. Studies of glacial clays of Wisconsin have shown that many of them contain calcium carbonate in quantity adequate to form an abundance of concretions. The Connecticut Valley clays seem to be actually siltstones or fine sandstones, a fact favoring the view that the concretions are epigenetic. This view is further supported by the distribution of the concretions, which occur mainly in the sandy layers in which the porosity is greatest. The flat disk-like shapes of the concretions are best explained as being due to the thinness of the sandy layers to which the concretions are largely restricted.

Concretions of chert and flint are largely confined to limestone and dolomite. They have usually been considered epigenetic in origin, the silica for their formation coming from the enclosing rock in which it had been deposited mainly as tests of organisms. This view has long been held by

[310] Sheldon, J. M. A., Concretions from the Champlain clays of the Connecticut Valley, 1900.

[311] Nichols, H. W., On the genesis of claystones, Am. Geol., vol. 19, 1897, pp. 324–329.

many British geologists, and it is supported by many of their American colleagues.[312]

Experimental work by Cox, Dean, and Gottschalk[313] suggested that solutions containing calcium carbonate in the presence of carbon dioxide would not be likely to acquire and transport colloidal silica, as these two substances are precipitants of silica. However, Lovering[314] has shown, and his conclusions have been checked by Moore and Maynard,[315] that it is only in solutions of relatively high silica concentration that calcium carbonate and carbon dioxide have any decided precipitating effect and that even then some silica remains unprecipitated. The presence of protective colloids may thoroughly nullify the effects of the carbonate and carbon dioxide. The studies of these three men indicate that solutions would have little difficulty in transporting silica into carbonate sediments.

Daly[316] states that the large calcareous concretions in the Devonian at Kettle Point, Ontario, were formed within the enclosing shale by displacing it, and that their formation antedated the development of the joints and the final consolidation of the shale. He states that the force of crystallization of calcite was the deforming agent that enabled the concretions to push the shale aside. Rominger, on the other hand, regarded the curvature of the beds around these concretions as evidence of the settling of the strata around an already solid structure.

The question arises as to the time of the epigenetic development of concretions. Is it antecedent to the solidification of the containing strata; contemporaneous therewith; or does it occur when, due to weathering or diastrophism, the strata have entered the zone of active ground-water circulation? It is probable that concretions are forming in all stages of a rock's history, but it is also probable that the maximum development is at the beginning and the end of that history, that is, that most epigenetic concretions develop before the containing strata are solidified and after these strata are subjected to the influence of active ground-water circulation. It is possible also that many flint and chert concretions develop during the

[312] Moore, E. S., Siliceous oolites and other concretionary structures in the vicinity of State College, Pennsylvania, Jour. Geol., vol. 20, 1912, pp. 259–269; Van Tuyl, F. M., The origin of chert, Am. Jour. Sci., vol. 45, 1918, pp. 449–456; Dean, R. S., The formation of Missouri cherts, Ibid., vol. 45, 1918, pp. 411–415.

[313] Cox, G. H., Dean, R. S., and Gottschalk, V. H., Studies on the origin of Missouri cherts and zinc ores, Bull. 2, Mining Experiment Station, Missouri School of Mines, vol. 3, 1916, pp. 9–15.

[314] Lovering, T. S., The leaching of iron protores, Econ. Geol., vol. 18, 1923, pp. 537–538.

[315] Moore, E. S., and Maynard, J. E., Solution, transportation and deposition of iron and silica, Econ. Geol., vol. 24, 1929, pp. 398–402.

[316] Daly, R. A., The calcareous concretions of Kettle Point, Lambton Co., Ontario, Jour. Geol., vol. 8, 1900, pp. 135–150.

process of weathering, just as the silicification of fossils[317] is related thereto, although the two processes of silicification are entirely different. (See discussion under chert and flint.) It is certain, moreover, that many iron-oxide and calcium-carbonate[318] concretions are formed in the zone of weathering above or near the water table.

Epigenetic formation of concretions requires that the composing material shall be brought from outside sources or be obtained from the enclosing formation. Rate of growth hinges upon availability of material, rate of movement of the transporting solution, its solvent ability, and the activity of the precipitating agent. The difficulties become apparent when these factors are studied in detail. When the type of rock is considered, it seems obvious that limestones and shales, because of general impermeability when far from the surface, are not promising hosts for the formation of epigenetic concretions under those conditions, and that sandstones are. However, when any rock enters the zone of weathering, its permeability, through the increase in size and number of divisional openings, is largely increased, and it becomes easier for epigenetic concretions to form therein. On the whole, however, field studies seem to furnish little evidence that concretions, other than iron oxide and calcite ones, are extensively developed in this zone.

Criteria for the Determination of Syngenetic or Epigenetic Origin. Criteria for the determination of time relationship to enclosing rock are few, and the same facts have been interpreted in opposite ways by different observers. Features bearing on the problem are: (1) curvature of beds around concretions, (2) lines of stratification passing through them, (3) fossils within or on concretions, (4) physical character of the enclosing rock, (5) volume of concretions, and (6) their distribution.

(1) Curvature of Beds around Concretions. Bedding planes may curve both over and under concretions, the former curvature usually being the more pronounced. Such curvature is most common in clays and shales, occurs rarely in thin-bedded limestones and dolomites; and usually is absent in sandstones and thick-bedded limestones. Curvature of bedding around concretions has been differently interpreted by different geologists. Daly[319] concluded that the Kettle Point concretions developed within or between the beds, forcing them apart and forming the curvature. Newberry[320] considered the curvature due to the shrinkage and settling of the shale beds around

[317] Bassler, R. S., The formation of geodes, etc., Proc. U. S. Nat. Museum, vol. 35, 1908, pp. 134–135; Bain, H. F., and Ulrich, E. O., Bull. 267, U. S. Geol. Surv., 1905, pp. 27, 30.

[318] Kindle, E. M., Range and distribution of certain types of Canadian Pleistocene concretions, Bull. Geol. Soc. Am. vol. 34, 1923, pp. 623–624.

[319] Daly, R. A., op. cit., 1900.

[320] Newberry, J. S., Geol. Surv. Ohio, vol. 1, 1873, p. 155.

the solid concretions. Tarr[321] reached a similar conclusion for the chert concretions in the Burlington limestones of Missouri, and to the same cause Sargent[322] assigned the curving about the concretions in the Carboniferous of Derbyshire. Salisbury[323] expressed the opinion that

> certain calcareous concretions in shale about which laminæ bend appear to be syngenetic. These concretions appear to have grown in a shale and to have bent laminæ above themselves and down beneath. In these cases laminæ are greatly thinned above the highest part of the concretions and below the lowest, while at the sides of the concretion between the bent laminæ there is evidence of space filled in, the filling showing laminæ. Laminæ bent above a concretion hereby seem to prove a syngenetic origin.

This is in harmony with the generalization of Sorby[324] that curvature of laminations about a concretion is due to consolidation and settling of sediments deposited during its formation. Richardson[325] found that laminæ of sediments deposited in thin layers over pebbles thickened and bent upward toward the pebbles and terminated against their sides. The major curvature was above. Layers beneath pebbles showed little bending downward, but a shallow depression was formed. However, this last characteristic would depend upon the character of the underlying materials. Syngenetic concretions in thick beds produced no characteristic that would indicate their origin. It would thus seem that thickening and bending upward of laminæ toward concretions, with some laminæ terminating against them, strongly suggest a syngenetic origin.

Curvature of laminæ around a concretion may also be developed by displacive growth, but, unless the concretion was very shallowly buried, the displacement would be more or less uniform above and below, and if growth proceeded uniformly in all directions beds at the sides of concretions should show crumpling or thickening in conformity with the pressure. No record of such has been found. Cone-in-cone is a common feature of many concretions, and the presence of this feature has been adduced as evidence of pressure connected with growth. However, until the factors responsible for development of cone-in-cone are known, it is idle to offer this feature as evidence for the epigenetic origin of concretions. Major curvature of laminæ above a concretion suggests, but by no means proves, a syngenetic origin.

[321] Tarr, W. A., The origin of the chert in the Burlington limestone, Am. Jour. Sci., vol. 44, 1917, pp. 409–452.

[322] Sargent, H. C., The Lower Carboniferous cherts of Derbyshire, Geol. Mag., vol. 58, 1921, pp. 265–278.

[323] Salisbury, R. D., Bull. Geol. Soc. Am., vol. 32, 1921, pp. 26–27.

[324] Sorby, H. C., Application of quantitative methods to the study of rocks, chap. 9, Concretions, Quart. Jour. Geol. Soc., vol. 64, 1908, pp. 205–220.

[325] Richardson, W. A., The relative age of concretions, Geol. Mag., vol. 58, 1921, pp. 114–121.

The slickensided surfaces of some concretions have been interpreted as due to settling of the material over the concretion and also to the growth of the concretion upward into the shale. Either seems possible.

(2) *Lines of Stratification Passing through Concretions.* Lines of stratifications passing through concretions have been held by most students as proof of epigenetic origin, it being thought that the concretions arose through local cementation of the enclosing rock. This is particularly obvious in concretions found in sandstones. Concretions of replacement ought to be common in carbonate rocks, and should also show these stratification planes, but, as a general rule, the concretions in carbonate rocks rarely show stratification planes or other structural features of the enclosing rocks. This does not prove a syngenetic origin, however, as it is not essential in replacement that such structural lines should be preserved. Lines of stratification are common in calcareous and ferruginous concretions in clays and shales. As such rocks are relatively impervious and the usual forms of the concretions are elliptical or discoidal, the aggregating agent is supposed to have followed the bedding planes. As a rule, there is little replacement and the concretions originated largely through cementation.

It is possible that laminæ in concretions might also be formed during the growth of the concretion if the growth was simultaneous with that of the enclosing bed, and the absence of nuclei in so many claystones is favorable to this view.

Concretions having horizontal laminæ that are discontinuous with those of the enclosing beds which in turn curve over the concretions would seem conclusively to be of syngenetic origin. Tarr[326] has shown this to be true of concretions in the Cretaceous shales of South Dakota and in the Lias of the Dorset coast of England.

(3) *Fossils within or on Concretions.* Observers have noted that the fossils in the centers of many concretions are wonderfully well preserved, even to the minutest detail. Such remains are the leaves and insects in the Mazon Creek concretions of Grundy County, Illinois; the fish brains in concretions from Pennsylvanian strata near Lawrence, Kansas; medusæ in the Middle Cambrian of Alabama; and the "Capelin" fish in concretions of glacial clays in Greenland.[327] It is probable that the organic matter in the concretion played an important part in causing the precipitation to which the concretion is due. This precipitation must have been initiated shortly after the organisms came to rest upon the sea bottom, and it is probable

[326] Tarr, W. A., Syngenetic origin of concretions in shale, Bull. Geol. Soc. Am., vol. 32, 1921, pp. 373–384. Article relating to the Lias in press.

[327] Guide to fossil reptiles, amphibians, and fishes, British Museum (Nat. Hist.) 1922, p. 98.

that all concretions containing excellent fossils are of syngenetic origin or, at least, that they were only very shallowly buried at the time of formation.

Fossils are also present within the other portions of concretions and upon their surfaces, and it is not uncommon that these fossils are almost the only ones occurring in a given formation, as are those in the Oneota dolomite of the upper Mississippi Valley. Such conditions suggest a syngenetic origin or, at least, only very shallow burial.

(4) *Physical Nature of the Enclosing Rock.* The physical character of the enclosing rock in which concretions occur has some bearing on their origin. The foremost factors are porosity and permeability, the latter being of greater significance, for unless the pores are connected there is little or no immediate passage of water.

Shales are decidedly impervious both to liquids and gases, but dissolved material may diffuse through them, and in the course of a long time perhaps some movement may take place. There is little chance for the development of replacive concretions in shales, but displacive and cementation concretions are possible. The carbonate rocks may be very permeable along certain lines; they are very soluble and hence they may be readily replaced. Sandstones are very permeable, but little soluble. Therefore, there can be little replacement in sandstones, and the concretions in them are largely the result of cementation.

(5) *Volume of Concretions.* A vital consideration with respect to supposed displacive concretions is the volume. The following table gives the approximate cubical contents of spheres of various diameters.

	cubic feet
2 feet in diameter	4
5 feet in diameter	66.5
10 feet in diameter	523

The introduction of an epigenetic displacive concretion of 2 feet diameter means that the surrounding rock must be sufficiently compressed to account for 4 cubic feet of volume. This may occur, but when the diameters greatly exceed 2 feet it does not seem possible to account for the concretions by any theory of displacement.

Concretions of syngenetic origin might attain any dimension, and upon burial the beds would curve over them in the manner described. Compression of the enclosing sediments would increase the curvature. In syngenetic concretions, volume has no significance. Volume considerations also have no significance in concretions of replacement or cementation.

(6) *Distribution of Concretions.* The common distribution of concretions along bedding planes may mean deposition in the interval between the formation of two strata. On the other hand, it may mean deposition of

material carried in solution by ground water which found easy passage along the bedding planes. The fact that concretions are not common along joint planes, however, suggests that the syngenetic origin is the more probable.

Summary

It is impossible to harmonize all occurrences of concretions with one theory of origin, and the composition, sources of material, aggregation, cause of deposition, form, internal structure, nucleus, external features, and character of the enclosing rock must be considered and evaluated in each case. In other words, each concretion presents an individual problem. Some concretions are certainly specialized cases of original deposition; others may equally well be the result of permeating water action.

CONE-IN-CONE

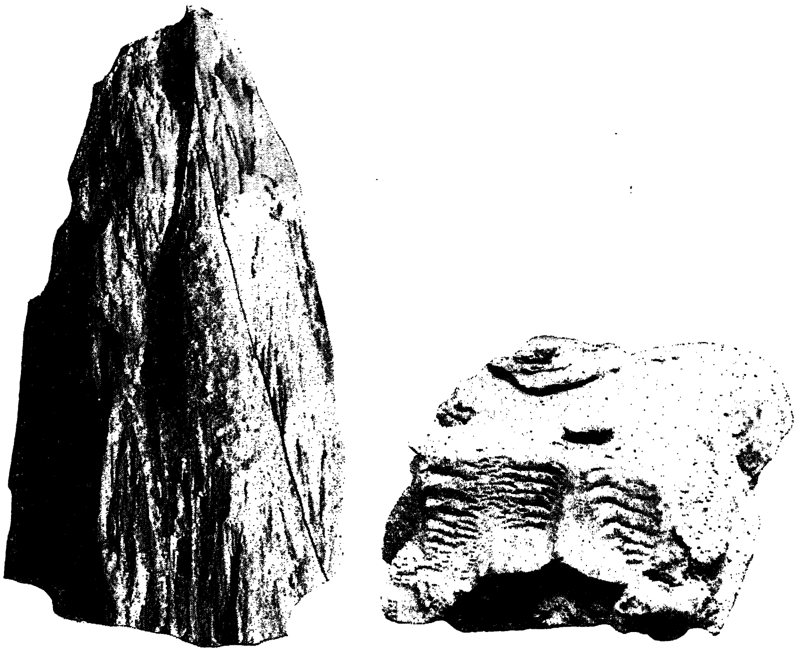
BY W. A. TARR

Cone-in-cone is a structural feature of sedimentary rocks that has attracted wide attention. It has been described by many authors whose descriptions are all very similar but whose ideas of its origin differ considerably. The first reference made to cone-in-cone is that by David Ure in his "History of Rutherglen and East Kilbride, Scotland," published in 1793. The cone-in-cone was found near Kilbride and was known to the miners as "maggy band." A fine specimen of cone-in-cone from the Carboniferous of Derbyshire in the British Natural History Museum is labeled "Petrificato Derbiensia" and is dated 1809. William Martin in describing it states that although it has been regarded as a fossil by some it is not, any more than fibrous gypsum is, but he offers no further explanation of it. Hausmann mentions tutenmergel (cone-in-cone) in 1812, and von Leonhard describes it in his "Charakteristik der Felsarten," 1823. S. P. Hildreth described cone-in-cone in the American Journal of Science in 1836 (vol. 29, p. 99) as a fossil, but James Hall in 1843 recognized it as inorganic material. Murchison illustrates cone-in-cone in "The Silurian System," 1839 (pl. 26, fig. 12), under the name "Cophinus dubius," supposing it to be a fossil zoophyte. His account of the structure and the evidence he advanced to prove its organic origin make interesting reading.

Description

Cone-in-cone structure usually consists of a nest of concentric cones, though some cones occur singly. Heights of cones range from 1 to 200 millimeters; those from 10 to 100 millimeters are most common. Basal diame-

ters depend upon the heights and angles of slope of the cones. In some cones, height and basal diameter approximate equality; ordinarily the diameter is less than the height. Apical angles range from 15 to 100°, with seemingly no dominant development for any angle in the range although angles of 30 to 60° are thought to be most common. Specimens of each occurrence seem to have more or less uniformity of angle. The apical angle is not always continuous, as some cones have flaring bases.



A B

FIG. 101. CONE-IN-CONE STRUCTURE

The cones in the larger specimen are about 5 inches long. The smaller specimen shows what seems to be a cone in process of being lifted out. The annular ridges and depressions are shown in *B*. Collected at Langley in southeastern Ellsworth County, Kansas, Lower Cretaceous. Photograph by Diemer, University of Wisconsin.

Sides of cones are usually gently ribbed or fluted, and some have the fine striations typical of slickensided surfaces. The ribs of a cone have counterparts on the enclosing cone. Most cones possess the "conic scales" of Gresley,[328] that is, conical laminæ which extend over only a part of the cone. The sides of the depression in which a cone rests are characterized by more or less discontinuous annular depressions and ridges which are parallel

[328] Gresley, W. S., Cone-in-cone, Quart. Jour. Geol. Soc., vol. 50, 1894, pp. 731–739.

to the surface of the cone-in-cone layer. These range in width from mere lines to five or six millimeters, and usually are a millimeter or less. Much smaller, but similar depressions occur rarely on the cones and are parallel to the bases. The annular depressions and ridges are largest in the upper part of the cone cup (and on the basal parts of cones) and become finer and finer nearer the apices. They are found in greatest widths and abundance on impure (that is, having a high clay content) cone-in-cone. Each depression is filled with clay, which may continue as films of various thicknesses between cones or between conic scales and cones. These various features are shown in figures 101–102.

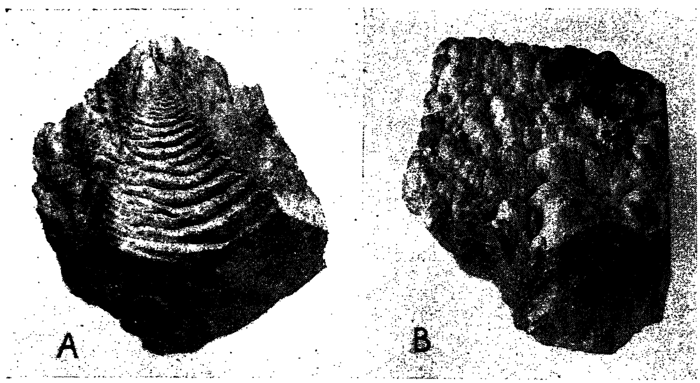


FIG. 102. *A*, CONE-IN-CONE SHOWING THE ANNULAR DEPRESSIONS AND RIDGES; *B*, BOTTOM OF CONE-IN-CONE SHOWN IN *A*

A. The circular areas on the surface shown at the bottom of the figure are bases of other cones.

B. This shows the bottom of the cone-in-cone of figure *A* and illustrates the development of the cone. The development of shear planes gives this specimen its cone structure. Both figures natural size. Photographs by W. A. Tarr.

The internal structure of cone-in-cone material is usually fibrous. The fibers are never terminated by crystal faces. In cross section, they are rudely circular. The fibers are parallel or inclined to the axis of the cone, and may or may not be parallel to its surface. Richardson[329] has described some simple types of cones having parallel fibers that are parallel to the cone axis and that terminate at the surface of the cone. The writer, also, studied these simple cones in the "beef" (which is a fibrous layer of calcite) on the southern coast of England and found that the *ends* of the fibers are actually parallel to the sides of the cone. Some cones an inch long, in which the fibers of the outer part of the cone are parallel to the sides, are part of a

[329] Richardson, W. A., Petrology of the shales with "beef," Quart. Jour. Geol. Soc., vol. 79, 1923, pp. 91–92.

layer of parallel fibrous calcite five inches long. Richardson states that the elongation of the calcite fibers in the "beef" is in the direction of the vertical (c) axis, and the mean value of the apical angle of the terminations of the fibers is nearly equal to that between the rhombohedral cleavages of calcite. The writer has measured the angles of the conical surfaces with the cone axis in a section of cone-in-cone made by Prof. T. G. Bonney from a specimen of the "beef" from the Isle of Wight and found them to range from 22 to 33°, averaging 30°. This is considerably less than the values noted by Richardson, and indicates that the angles may depart widely from the rhombohedral cleavage angle of calcite. Parting planes occur in some cone-in-cone layers and in the materials studied by Richardson, Twenhofel, and the writer the fibers and the cones end abruptly at such planes.

Cone-in-cone structure occurs also, however, in massive material, though the following description of it is the first that has been given anywhere. Cone-in-cone in massive material was first studied by the writer in Sedgwick Museum at Cambridge University, the material coming from the Coal Measures of Tipton near Dudley in Staffordshire. These cone-in-cones are splendidly developed, showing all the usual external features of those occurring in fibrous materials. The annular depressions are minutely developed on some cones, no less than 43 having been counted in the space of one-half inch. The bases of the cones show a remarkable system of concentric lines that mark the development of the cone-in-cone structure. These lines are similar to those formed by pressure in testing materials. Many of the cones have sharp apices and flaring bases. (The cone-in-cone Murchison described is in a similar massive material.)

Other cone-in-cone structures in massive material that have since been studied by the writer occur in Perry County, Kentucky, and in western Kansas. The Kentucky material has a marvelous series of cones (fig. 103). The material from Kansas is an impure chalk or marl and likewise has well developed cones but not such completely nested series. The annular depressions are very small in these specimens.

Undoubtedly, the most remarkable conical structures known are those that occur in the coal of Monmouthshire, England, and in southern Wales (see fig. 104). These cones never occur singly but are united to form curved parallel ridges. The cones average 38 to 40 millimeters in height, and their apical angle is 36°. Their sides are brilliantly slickensided, and bear occasional tiny chatter marks. Conic scales occur on the cones, also. There are two sets of cones, with their apices pointing in opposite directions and their bases separated by a thin layer of shale or coal.[330]

[330] Garwood, E. J., Geol. Mag., vol. 29, 1892, pp. 334–335; Gresley, W. S., Geol. Mag., vol. 29, 1892, p. 432 (does not consider this cone-in-cone).

FIG. 103. CONE-IN-CONE DEVELOPED IN A FINE-GRAINED MASSIVE LIMESTONE

There should be noted the repeated series of cones and the uniformity of the shape, features characteristic of cones in such materials. From the Pennsylvanian of Perry County, Kentucky. Specimen given by Professor A. C. McFarlan. Natural size. Photograph by W. A. Tarr.

Another type of cone structure should be mentioned for the sake of completeness, although it is probably rare. This type is a percussion cone occurring in pebbles of a fine-grained quartzite. The specimen in the writer's possession was found by Sidney Powers on Bear Creak, south of Bozeman,

FIG. 104. CONICAL STRUCTURES IN COAL FROM MERTHYR TYDVIL, WALES
Specimen in Brighton Museum, England. Photograph by W. A. Tarr.

Montana. The apices of the cones are at the surface of the pebble, which is covered with concentric fractures that intersect and cross each other at various angles. The angle between the smooth sides of the cones is 53°.

A percussion cone in quartzite occurring near Birmingham, England,

is in the British Museum. This cone has approximately a 90° apical angle. Another mechanical cone formed in chert from Antrim, Ireland, is in the same museum and has a very similar shape. French[331] in studying the fractures developed in homogeneous media found that percussion cracks on the surface were concentric, and that the resulting cone with its internal apical angle of 90° had its apex at the surface. Light blows produced the best circular fractures and cones. In some media, radial fractures were developed from the point of contact. These cones show that percussion can produce cones, but it should be noted that the apices and not the bases are at the surface. In the calcite, it is the cleavage that causes the base of the cone to develop at the surface.

Composition

Most cone-in-cone is largely composed of calcium carbonate in the form of calcite; the amount of $CaCO_3$ ranges from 60 to 98 per cent and the remainder is mostly clay. Cone-in-cone composed of gypsum is present in the Comanchean of south-central Kansas; this is probably best regarded as a replacement of calcite or aragonite. It has been suggested that some cone-in-cone is composed of aragonite, but the writer has found none, and Twenhofel reports a similar fact. Cone-in-cone might very well be composed of siderite, as the structure has been reported in association with ferruginous concretions, but no cones of siderite have been described.

Mode of Occurrence

Cone-in-cone structure is most common in shales and marls. It occurs also very commonly in association with concretions. It may form a layer both above and below a concretion and usually does not extend beyond it. Cone-in-cone layers may be persistent or they may be lenticular in character. Small lenses and plates are common in some formations. The layers of cone-in-cone may be single with the apices of the cones all pointing downward, or they may be double in which case the apices of the cones in each layer point toward each other. In cone-in-cone occurring at the ends of concretions or in disturbed material, the apices of the cones may point in any direction. In one remarkable aggregate of cones studied by the writer, the long axes of the cones were horizontal and the apices pointed in every direction in the horizontal plane.

Cone-in-cone is also associated with beds of limestone and may be coextensive with the limestone or only in connection with a part of the bed. The Comanchean of central Kansas has a single cone-in-cone layer extending for 40 miles in a northeast-southwest direction and for 25 miles at right

[331] French, J. W., Trans. Geol. Soc. Glasgow, vol. 17, pt. 1 (1919-1922), pp. 50–68.

angles to that direction. In places, the bed assumes a nodular aspect. Well developed cone-in-cone occurs in about 70 feet of marine shales (known

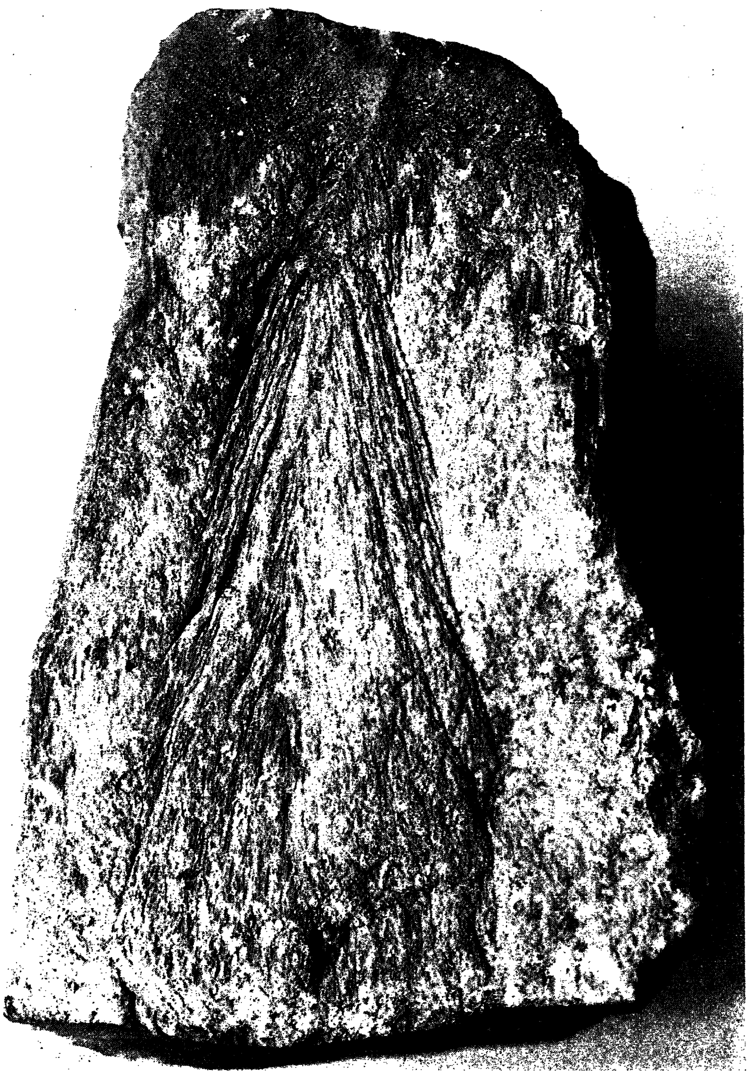


FIG. 105. CONE-IN-CONE FROM THE "SHALES WITH 'BEEF'"

Collected by W. A. Tarr from the Lias below Black Ven Cliff east of Lyme Regis, Dorset, England. Natural size. Photograph by W. A. Tarr.

as the "shales with beef") in the Lias on the Dorsetshire coast of England.[332] The cone-in-cone is well developed in more than twenty-five persistent layers of the fibrous calcite ("beef") and in many more that are more or less impersistent. In some of these layers, concretions are enclosed between a double band of cone-in-cone. Some of the horizons are marked by lenticular cone-in-cone units, and others carry concretions surrounded by cone-in-cone layers. The overlying shale beds also contain fibrous layers of calcite and concretions with cone-in-cone (figs. 105–106).

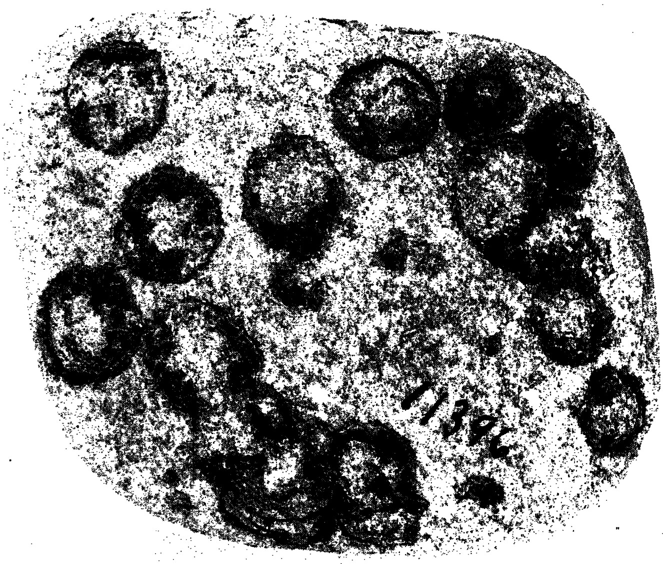


FIG. 106. TOP OF A SPECIMEN FROM THE "SHALES WITH 'BEEF'"

Collected by W. A. Tarr at a locality east of Lyme Regis, Dorset, England. The distribution of the cones in the "beef" should be noted. The cones extend to the shale parting of the "beef," a distance approximately the same as the diameter of the base of the cones. Photograph by W. A. Tarr.

Geographical and Geological Distribution

It is probable that cone-in-cone has a rather general distribution over all continents. In the United States, it was early reported from western New York, Pennsylvania, and Ohio. It occurs also in the Pacific Coast region. It is known to have a considerable distribution in England, France, Germany, and other parts of Europe.

[332] Lang, W. D., Shales with "beef," a sequence in the Lower Lias of the Dorset coast, Quart. Jour. Geol. Soc., vol. 79, 1923, pp. 47–66 (52–53, and fig. 2).

The oldest geological occurrence of cone-in-cone that has been reported is in the Middle Cambrian of Utah. It is present (in the Arisaig section) in the Silurian of the St. Lawrence region; the Devonian of New York, Pennsylvania, Ohio, and Michigan; the Carboniferous of the Appalachian and mid-continent regions, and many parts of Europe; the Permian of Kansas, Montana, and elsewhere; the Jurassic of Europe; the Cretaceous of the Great Plains region; and the Tertiary of many parts of the world.

Origin

Great difference of opinion has been expressed with respect to the origin of cone-in-cone, and there is also difference of opinion concerning the time of its development. Views relating to origin may be placed in three categories: (1) those representing the structure as a consequence of gas rising through unconsolidated sediments; (2) those holding that it is a form of crystallization; and (3) those holding that the cones were caused by pressure due to the weight of the overlying sediments, or to pressure connected with the growth of the associated concretions.

(1) The gaseous theory has little support. Its chief advocate was Young,[333] and it is not known that it has any adherents at the present time. It was Young's view that gas generated in unconsolidated sediments produced the cones in a surface or near-surface layer through which the bubbles passed as they rose to the surface. Thus, the structures were, under this theory, essentially contemporaneous with the sediments in which they occurred.

(2) There have been a number of supporters of the crystallization theory. Many minerals are known to crystallize in fibrous form; such is a common occurrence of calcite in pisolites, oolites, and veins. Spheres having radially directed fibers are well known, and veins and layers with fibrous minerals are not uncommon, but it has been difficult to understand how crystallization could develop such a complex structure as cone-in-cone. Sorby[334] seems to have been the first to advocate this origin, explaining the cones as the result of radial crystallization around an axis. This hypothesis was also advocated by Cole,[335] who maintained that the clay between the cones was the residue forced aside during the crystallization of the calcite.

The latest advocate of the crystallization theory is Richardson,[336] who states that there are three essential facts bearing on the origin of the cone-in-cone structure in the shales with "beef:" (1) limitation of cone-in-cone

[333] Young, J., Geol. Mag., vol. 29, 1892, pp. 138, 278, 480.

[334] Sorby, H. C., On the origin of cone-in-cone, British Assoc. Adv. Sci., vol. 29, 1859, p. 124; The Geologist, vol. 2, 1859, p. 485.

[335] Cole, G. A. J., On some examples of cone-in-cone structure, Mineralogical Mag., vol. 10, 1893, pp. 136–141.

[336] Richardson, W. A., op. cit., 1923, pp. 92–95.

to the fibrous or acicular calcite (this limitation is now known to be incorrect, as the descriptions above show); (2) direct increase in complexity of cones with the increase in thickness of cone-in-cone layers; and (3) penetration of a cone-layer ("beef"-veins) as a whole, by the cones without regard to internal structure. The writer does not agree with this last statement as his studies of the shales with "beef" showed that the cones were on both sides of the parting but did not cross it. Richardson thinks that the cone-in-cone is due to internal stresses set up during the crystallization of calcite in fibrous form. During this crystallization, the load was that of the overlying strata with some minor deductions which need not be considered. This load produced a vertical stress. In the horizontal planes, lateral stresses were generated by resistance to the lateral growth of the fibers. These two sets of stresses produced conical surfaces of maximum shear, the apical angles of the cones being determined by the relative magnitude of the stresses. The inclination of the perfect rhombohedral cleavage to the vertical axis of the fibers would probably render them extremely sensitive to the conical surfaces of shear. Richardson thinks that "Where master shear-planes were established, fibers already formed might be fractured; but, more probably, the action would be to inhibit growth in such a way that the fibre could not cross the plane." Spacing of shear cones, he thinks, would be due to many factors difficult to evaluate.

The writer believes that the "beef" layers are the result of the redeposition of the calcium carbonate of the associated marls (most of the so-called shales are marls). The deposition of the fibrous calcite started along a bedding plane, and as the solutions carried more calcium carbonate to this plane growth continued in both directions from the plane. This method of growth could not produce pressures in the growing fibers, however, as their growth was entirely vertical, proceeding only from the exposed ends of the fibers. The crystalline fibrous calcite undoubtedly occupied less space than did the original marl. In this transference of the $CaCO_3$ of the marl to the "beef" layer, the associated clay was left behind and formed the "paper shales" described by Lang.[332] Lang states that "the upper division (of the shales with 'beef'), some 30 feet thick, consists of paper-shales, is of a brown rather than blue colour, and has more numerous beef-seams than the lower division." This association is in keeping with the writer's theory of the origin of the "beef." There is no support for Richardson's assumption that lateral growth of the fibers produced horizontal stresses, because after growth was once started they *grew upward* and not laterally. Richardson's sketches (ibid. pp. 91 and 92) show this, for he represents the fibers as being parallel sided.

Furthermore, the time of development of the cone-in-cone is a fundamental

factor in its origin. Richardson says nothing about the time, but does furnish time proof against his own theory. He postulates stresses, induced by supposed lateral growth, which are thought to act with vertical stresses (load) to produce a shear plane. As the mass of fibers grew, this shear plane was supposed to continue *upward*, separating the *new growth* from the old, a physical impossibility, as Richardson actually admits (ibid. p. 94). Furthermore, his own sketches (ibid. fig. 4, p. 89 and fig. 5, p. 91) prove that the *cones* must have formed after the layer had completed its growth as he shows the cones crossing from one side to the other (an assumption, however, with which the writer does not agree) and such a development is impossible during growth. Further evidence against Richardson's theory is that cone-in-cone occurs in very thin layers of "beef." Stresses that would aid in forming cones could not develop in layers $\frac{1}{16}$ inch thick.

The evidence, not only in the cone-in-cone in the "beef" but in that of many other localities where the writer has studied it, shows that the *cones are always later than the fibrous layer in which they occur.* This is proved by the following facts: (1) cone-in-cone is irregularly distributed (uniformity should be the rule if cone-in-cone was due to crystallization) within a layer; (2) the cones develop universally in the *outer part of the fibrous layer and with their bases at the surface*; and (3) the evidence is positive that the cones have moved downward (or upward) and that solvent action has accompanied the movement.

The writer believes, however, that Richardson's point about the relationship between the cleavage of calcite and the angular forms of cones is of value in explaining the true origin of cone-in-cone. Likewise, pressure is essential in explaining the origin, but the writer does not agree that the force developed by crystallization was a factor.

(3) The pressure theory was developed in considerable detail by the writer[337] in 1922. It was shown that nearly all cone-in-cone bears evidence of movement of the cones with respect to each other; (1) in the displacement of horizontal bands, and (2) in the penetration of an inner cone into an outer without breaking the surface of the latter (the place of the inner cone is thus indicated on the base by a depression). It should be added that the faintly developed slickensided surfaces seen on some cones, and the general occurrence of striations are further evidence of movement of cones within cones. Solvent action accompanied the movement of the cones, for otherwise the outer cones would have been destroyed. Further evidence that solution must have occurred is the clay in the depressions on the inner surfaces of cones (actually in the cone cups), and the films of clay over the surface between the depressions. This clay is the insoluble residue of the cal-

[337] Tarr, W. A., op. cit., 1922, pp. 205–213.

cite that was removed in solution. This residue is analogous to that on the ends and sides of stylolitic columns. It can scarcely be doubted that the movement was due to pressure, which may also have been an aid in the solvent work.

The two facts of movement and solution in connection with cone-in-cone are fundamental and must be accounted for in explaining the origin. The cones in coal and in quartzite involve only movement in their formation, but they are the only exceptions to the rule that movement and solution have both been involved in the formation of cone-in-cone. In the writer's previous paper (ibid. p. 332), he stressed the fibrous character of the material, regarding it as essential. It is true that the greater part of all cone-in-cone occurs in fibrous material, but the discovery that cone-in-cone has developed in massive material has shown that the fibrous character is not essential. It is undoubtedly an important factor, however, when present. The position of the fibers in a layer is also a factor, for the cone axis is usually parallel to the elongation of the fibers. Another important factor to be considered is the closeness of the cleavage angle of calcite to the angle of the fracture produced by any outside stress, as discussed by Richardson.[336] In the writer's opinion, this factor has more value in the pressure theory of the development of cone-in-cone than it does in Richardson's application of it to crystallization.

The source of the pressure is the most difficult factor to explain. Possible sources of pressure previously suggested were the change of aragonite to calcite (assuming the original fibrous mineral was aragonite), a change that involves a volume increase of 8.35 per cent; the growth of concretions associated with cone-in-cone; the pressure of overlying beds; and diastrophic movements. As was stated in the writer's original article, the conception of the importance of one or all of these factors might be revised or discarded altogether after further study, and this has proved to be true.

If it could be shown that the original form of the calcium carbonate was aragonite, as was assumed by some men in earlier studies, a source of considerable pressure would be available. Neither the writer nor Twenhofel, who has also examined many cones, has ever found any that consisted of aragonite. In his original paper, the writer cited what appeared to be corroboratory reasons for thinking that the original form might have been aragonite but he does not now believe they have much weight for the following reasons: cone-in-cone is not confined to fibrous material, and the fibers in both the original layer and the cones are usually parallel and but rarely radiating. Furthermore, it is just as easy to explain the initiation of conical forms by pressure as to explain how and why the change to calcite from aragonite should result in conical forms.

The possible growth of associated concretions as a source of pressure was discarded before, as vast numbers of cone-in-cone structures are unassociated with concretions, and because the concretions associated with cone-in-cone in the Dakotas and Wyoming, as well as those with the "beef" of the Lias in England, have been shown (by the writer) to be syngenetic, whereas the cone-in-cone is unquestionably later.

Diastrophic disturbances might induce various strains and stresses in fibrous calcite that would favor fracture and the formation of cones; but, as the majority of cone-in-cone structures occur in undisturbed formations, such a source of pressure is not of wide application.

The remaining sources of pressure are those due to the weight of overlying beds and to crystallization. As was pointed out above, the development of the cones must have followed the cessation of crystallization, for the bases of the cones are at the surface of the layer. Moreover, *the cones cut across the fibers near the surface*, a condition that could take place only after the fibers had formed. Thus, crystallization is eliminated as a source of pressure, though it will be shown later that some secondary (post-cone in time) deposition has taken place, producing certain features.

The weight of overlying beds is thus the remaining source of pressure, although previously it was not regarded as important. Reasons for believing in a differential vertical pressure due to overlying materials as a cause of cone-in-cone are as follows: (1) the great majority of cone-in-cone structures occur in horizontal, or what were originally nearly horizontal, beds; (2) the cones are dominantly on the upper side of a layer with their bases upward, though smaller ones occur also on the lower side, with their bases downward; (3) the most perfect cones have apical angles that approach those of the ideal cones developed in testing the crushing strength of materials, that is, angles of 70 to 110°; (4) the apical angles in cone-in-cone are nearly that of the rhombohedral cleavage of calcite (the cleavage of calcite would give an apical angle of 106°); (5) solution and rearrangement of the fibers occur along the minor fault planes that cut the fibers, parallel depressions developing on the lower side of the fault plane just as in the cone-cups; (6) layers with parallel fibers show stylolites, which are recognized as being due to differential pressure and solution; (7) sharp blows of a hammer on fibrous calcite produce percussion cones with angles that approximate many of those in cone-in-cone; (8) the surface of a layer of fibrous calcite containing cone-in-cone commonly shows concentrically curved fracture lines that are the result of pressure (these lines can be seen on a polished basal surface and in polished sections of the cones); and (9) the increasing pressure of overlying beds during their accumulation (1000 feet of average rock exerts a pressure of 1,100 pounds per square inch) and its *constant* application induced stresses

within the fibers that eventually resulted in fracturing which made possible the solvent work. There is far more reason for believing that the pressure that developed cone-in-cone was due to the weight of overlying beds than there is that it was due to the force of crystallization, as the latter force was exerted only *during the growth* of the calcite and the *cone-in-cone was developed after calcite fibers had ceased growing*. If crystallization had been a factor, cone-in-cone should occur on the upper and lower surfaces of *all fibrous calcite layers*, for the very elements of the theory demand that the effects of crystallization must be active everywhere during growth. The enormous number of fibrous calcite layers that are free from cone-in-cone is ample proof that crystallization is not the cause of its formation. Furthermore, as was pointed out before, the growth of the fibers takes place at their *outer ends* and hence the crystallization could not be the cause of the development of stresses, either vertically or laterally.

Localization or uneven distribution of the vertical pressure along the top of a layer was probably due to (1) varying density of the material immediately overlying it (dense material would transmit the vertical pressure most effectively), and (2) irregularities on the surface of the fibrous layer. Purely as a contributing factor, an earthquake vibration passing rapidly through the rocks might possibly have caused the release of the stresses induced by the slowly accumulating pressure. This may seem fanciful, but we need to correlate more factors of this type.

Minor elements that influence the development of cone-in-cone are the position, size, and shape of the calcite fibers. Perfectly parallel fibers are rare. They vary, likewise, in size and shape, becoming thicker as they grow outward, but conforming to the influence of the rate of growth of surrounding fibers. Some fibers are long slender columns; others taper on one end or both ends; and others are spindle shaped, although rudely circular in cross section. In layers two inches thick (a very common thickness), few of the fibers are continuous through the entire layer, as some pinch out and others are initiated alongside of them. Rapid growth would favor a tendency toward radiating structure, but as no specimen of fibrous calcite in the writer's collection shows a radial arrangement, he concludes that growth was largely a uniform process. In some specimens, closely spaced joints have broken a fibrous calcite layer into numerous polygonal columns along which solution work has produced thin rods with cones at the ends. Some long slender cones starting with a base one-half to three-fourths inch across have been reduced to columns one-quarter inch in width. This change from the typical pressure cone at the base to the slender column is due to the downward deflection of the shear plane by the vertical joint planes between the fibers, the process continuing until the sides of the column are

nearly (in some specimens actually) parallel to the fibers. The spindle shape of some fibers also aids in the downward deflection of the sides of cones. It is in this way that the long slender columnar cones are developed. The larger the fibers the greater is the ease of downward deflection. In very fine fibrous material and in massive material, the cones formed have a uniform slope from the apex to the base as there is less downward deflection. Cones in massive material would have to be entirely due to pressure, as were those conical structures formed in coal and quartzite. In one specimen of cone-in-cone in a massive marl, the cone-cup has splendidly developed rings and other features, showing that these features develop in massive materials. The angles are similar to those of cones formed in crushing tests.

The other factor aiding pressure in the formation of cone-in-cone is the work of solutions. Acting along the shear planes, they remove material, leaving behind an insoluble clay residue. In some specimens, this residue is minutely micaceous, which favors slipping along the shear plane. The annular depressions of the cone cups are the result of solution of the *ends* of the fibers surrounding the cone. Solution takes place there because the upper ends of the fibers are under pressure. Once started, growth of the annular depressions continues downward, just as solvent action at the end of stylolitic columns causes their further development. The circular character of the depressions is due to the fact that each successive group of fibers down the sides of the cone cups forms continuous rings around the cup (fig. 107). Solutions moving along this shear plane attack the upper thin edges of the fibers first and continue the solvent action downward. Variations in the position, size, and composition of the fibers, along with variation in the character of the solvent, account for the discontinuity of the annular depressions. The carbon dioxide content of the solution, as well as the rate of downward movement, probably has something to do with the effectiveness of the solvent action. Another factor in the localization of the annular depressions would be the formation of the tiny chatter marks. The distribution of pressure along the sides of the cones would also be a factor, solution occurring where the grains or fibers are under the greatest pressure. In the massive material, chatter marks and the rate of penetration of solutions are the probable localizing factors.

The $CaCO_3$ removed may be carried downward and deposited in cracks as veins or even in septaria. Some interesting lenses of cone-in-cone on the surface of large concretions in the Lias on the south coast of England are connected by cracks (now veins of calcite), with septaria below, making it evident where the dissolved material has gone. Other results of solution work are shown in the convergence at the apices of the cones of what were originally parallel fibers. This convergence is due to the removal of part

of the fibers, thus permitting their deflection. Further proof of the solvent action is the higher percentage of insoluble residue between the fibers at the apical end of the cones. The shift of originally parallel fibers to a position paralleling the surface of the cone must be due to pressure, coupled with deflection due to removal of *some* of the $CaCO_3$ of the fibers. Cones within cones would produce the same effect, and we have already pointed out that pressure can induce one inside the other. The rounded, blunt apices are the result of solution work.

Cones not uncommonly extend above the surface of the layer. This is caused by the redeposition of $CaCO_3$ along the shear plane, resulting in the actual lifting upward of the cone (fig. 101). In some cones, secondary layers of calcite one-eighth inch thick occur. This deposition took place

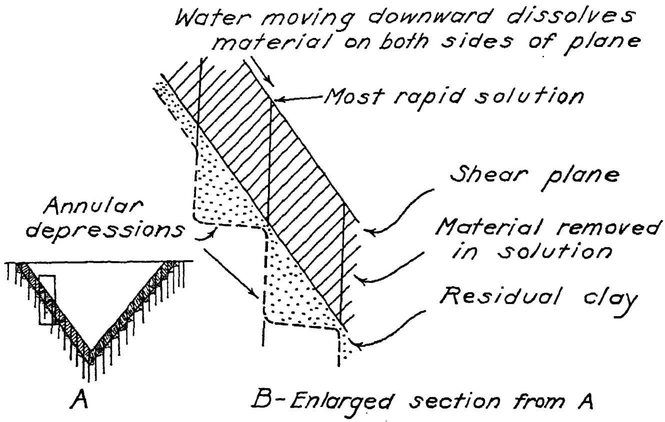


FIG. 107. DIAGRAM TO SHOW HOW SOLUTION ACTS ALONG A SHEAR PLANE, REMOVES SOME MATERIAL, AND DEVELOPS THE ANNULAR DEPRESSIONS IN THE CONE CUP

in the spaces between the cone and the cup, as the entrance of the saturated solutions was possible there.

Summary

Cone-in-cone is an epigenetic structural feature, characteristic of fibrous calcite layers (it is found rarely in massive material), in which it was induced by pressure that created conical shear surfaces. The angle of the shear surfaces to the elongation of the fibers varies widely, but in most cones it is closely similar to the rhombohedral cleavage angle of the calcite fibers, or to the typical angle in cones produced in crushing structural materials. Solvent work by ground water along these shear surfaces removes some $CaCO_3$, permits further movement of the cone (as is shown by displaced original features) and leaves the insoluble material in annular

depressions around the sides of the cone cup. A combination of pressure and solution induces movement and causes the formation of one cone within another. Without the accompanying solvent action, the movement would have caused a disruption of surrounding materials. It is the fibrous character of the calcite together with its rhombohedral cleavage that permits the development of cone-in-cone instead of stylolites, which develop in limestone in which the calcite grains are irregularly arranged. Pressure and solution, causing movement, are responsible for the formation of both cone-in-cone and stylolites, and in both of the structures the insoluble residues are present as evidence of the solvent action.[338]

STYLOLITES

Description

Stylolites[339] consist of vertically striated columns, pyramids, or cones on bedding planes, composed of the same material as the rock of which they are a part. Each column usually has a thin cap of dark clay, and the sides may be covered with similar clay, but in much less thickness. The stylolites on any given bedding plane have counterparts on the bedding plane above or below (fig. 108). A stylolitic bedding plane or seam may pass laterally into one without this structure, but on which there may be a layer of clay similar in composition to that associated with the stylolites.

Columns range in length from 1 mm. to over 30 cm.; average lengths are

[338] Other articles describing cone-in-cone are: Barbour, C. A., Publ. 7, Nebraska Acad. Sci., 1897, pp. 36–38; Bonney, T. G., Mineralogical Magazine, vol. 11, 1895, pp. 24–27; Broadhead, G. C., Science, vol. 26, 1919, p. 15; Chadwick, G. H., Bull. Geol. Soc Am., vol. 32, 1921, p. 26; Daintree, R. Quart. Jour. Geol. Soc., vol. 28, 1872, p. 283; Dawson, J. W., Acadian geology, 1868, pp. 676–677; Geikie, A., Textbook of geology, 4th ed., 1892, p. 421; Grabau, A. W., Principles of stratigraphy, 1913, pp. 788–789; Gresley, W. S., Geol. Mag., vol. 24, 1887, pp. 17–22; vol. 29, 1892, p. 432; Grimsley, G. P., Michigan Geol. Surv., vol. 9, 1903–04, pp. 100, 109; Hall, J., Nat. Hist. New York, Geol. 4th Dist., 1843, pp. 131, 192, 220, 230, 232; Harnley, B. J., Proc. Kansas Acad. Sci., vol. 15, 1895, p. 22; Harker, A., Geol. Mag., vol. 29, 1892, p. 240; Hildreth, S. P., Am. Jour. Sci., vol. 29, 1836 pp. 99–100; Jukes, J. B., Manual of geology, 1872; Keyes, C. R., Proc. Iowa Acad. Sci., vol. 3, 1898, pp. 75–76; Leonhard, K. C. von, Characteristik der Felsarten, 1923, p. 418; Marsh, O. C., Proc. Am. Assoc. Adv. Sci., vol. 16, 1867, p. 142; Murchison, R. G., The Silurian System, 1839, pp. 199, 206, 697; Newberry, J. S., Geol. Surv. Ohio, vol. 1, 1873, p. 211; Geol. Mag., vol. 22, 1885, pp. 559–560; Reis, O. M., Ueber Stylolithen, Dutenmergel und Landschaftenkalk, Geognost. Jahresh. d. k. bayer. Oberbergamt in München, Bd. 15, 1903, pp. 157–279 (250); Abstracts in Geol. Zentralb. Bd. 4, 1903–04, pp. 369–371; Zeits. f. Pract. Geol., Bd. 12, 1904, pp. 419–422; N. Jahrb. f. Min. etc., Bd. 2, 1906, p. 201; Sach, A. J., Geol. Mag., vol. 29, 1892, p. 505; White, C. A., Am. Jour. Sci., vol. 45, 1868, pp. 401–402; Young, J., Trans. Geol. Soc., Glasgow, vol. 18, pt. IV, 1886, pp. 1–27.

[339] The name is derived from the Greek *stylos*, a column, and *lithos*, a stone. In the preparation of this topic extensive use has been made of the studies of Doctor P. B. Stockdale, Stylolites: their nature and origin, Indiana Univ. Studies, vol. 9, 1922, pp. 1–97.

about 20–100 mm. The extent of a stylolitic seam is in proportion to the height of the stylolites, a seam with large stylolites having, as a rule, greater extent than one with small. Small and large stylolites occur in association. Associated with a layer of stylolites are numerous small, sharply intertoothed seams or sutures, the "Drucksuturen" of the Germans. Except in the matter of dimension, "Drucksuturen" are like the stylolites, into which they pass by gradual transition. The tops of stylolites have variable dimensions. Some are broad and flat; others are rounded; and still others are pointed or consist of a number of points. There seems little relation between the shape of a stylolite and its height, some being very broad and

FIG. 108. A TYPICAL, LARGE STYLOLITE-SEAM IN THE SALEM LIMESTONE OF THE DARK HOLLOW DISTRICT, LAWRENCE COUNTY, IND.

Note the irregularity in length and width of the interpenetrating parts. The darker, upper stratum is blue stone; and the lower buff. Note the small, minor stylolite-seam running across the column below *X*. The clay parting is plainly visible. The upper and lower strata are distinctly lithologically different. The longest column is about 9 inches. After Stockdale.

also very short, others broad and long. Diameters range from 1 to about 60 mm., 3 to 20 mm. being common.

Stylolites are usually straight, but occasionally curved examples occur. Instances are known in which one column cuts across another,[340] and small stylolite seams penetrated by large stylolites of an adjacent seam are not uncommon. The surface of a stylolite seam, that is, the surface produced by separating a seam into its two parts, is extremely irregular, with pinnacles, ridges, domes, etc. of highly variable orientation, height, and shape.

[340] Wagner, G., Stylolithen und Drucksuturen, Geol. und Pal. Abh., Bd. 11, Heft 2, 1913, pp. 101–128.

The clay cap on the end of a stylolite column, cone, or dome is always present, and it may attain a thickness of 10 to 15 mm. It has the composition of the insoluble residue in the rocks of which the stylolites are a part. The cap thins out down the side to thicken again beneath the adjacent downward-projecting stylolite. It seems probable that this clay represents insoluble residue of material dissolved in stylolite formation.

Sides of stylolites are always striated, with the ridges and grooves parallel to the direction of penetration of the structure. In some cases the sides have the appearance of being slickensided. The striations range from mere lines to deep grooves, the sides often appearing fluted.

Stylolite seams range from a few millimeters apart to many feet. In some examples two or more seams unite to form one, occasionally cutting across laminæ to unite in this fashion, and Gordon[341] describes stylolite seams as forming "a network intersecting the stone in all directions." Where stylolites cut across bedding and lamination planes, these end at the stylolites without upward or other deflection.

Stylolite seams tend to be horizontal, but inclinations as great as 45° or more are known. Most of them follow stratification planes. Stockdale[342] notes a stylolite seam following what seems to be a fault plane cutting the bedding at an angle of about 60°. Stylolites usually are perpendicular to bedding and fracture planes, but in inclined bedding the stylolites tend to have vertical or other directions instead of perpendicularity to bedding planes. Examples of such arrangement are found in the steeply inclined strata of some of the coral limestones of northern Indiana.[343] Such orientation has also been described by Fuchs,[344] Reis,[345] Wagner,[346] Gordon,[347] and probably others.

It has commonly been stated that stylolite columns have a fossil shell on the summit of each, this shell being a responsible factor in the formation of the column. It is, however, difficult to see the basis for this statement, as the columns on which shells are present are few. In other words, the presence of the shell is incidental and not causal. Shells partially or wholly penetrated by a stylolite are not uncommon; Stockdale[348] has described large

[341] Gordon, C. H., On the nature and structure of the stylolitic structure in Tennessee marble, Jour. Geol., vol. 26, 1918, pp. 561–568.

[342] Stockdale, P. B., op. cit., 1922, p. 44.

[343] Stockdale, P. B., op. cit., 1922, p. 54.

[344] Fuchs, T., Über die Natur und Entstehung der Stylolithen, Sitz. d. k. Akad. d. Wiss., Wien, Math.-Natur. Kl., Bd. 103, 1894, pp. 673–688.

[345] Reis, O. M., Über Stylolithen, Dutenmergel und Landschaftenkalk, Geognost. Jahresh. d. k. bayer. Oberbergamt in München, Bd. 15, 1903, pp. 157–279.

[346] Wagner, G., op. cit., 1913.

[347] Gordon, C. H., op. cit., 1918, pp. 564–565.

[348] Stockdale, P. B., op. cit., 1922, pp. 62–63.

shells so penetrated and a stromatoporoid into which five stylolites have extended.

Stylolites are best developed in limestones and dolomites, but they have been found in quartzite and shale.[349] They occur in limestones and dolomite of all ages and are particularly well developed in the Niagaran limestones of New York, the Paleozoic limestones of the Cincinnati Arch region and the Michigan basin, the Mississippian limestones of Indiana and Missouri, and the Tennessee marble of Knoxville, and a rock long famous for its stylolites is the Muschelkalk of Germany.

Stylolites were first noticed in 1751 by Mylius, who described them as "Schwielen" and stated that they resembled petrified wood. They were later described in 1807 by Freiesleben[350] as "Zapfenförmige Struktur der Flözkalksteine." The name originated with Klödin,[351] who considered that he had a fossil, which he described as *Stylolites sulcatus*. They were first noted in America by Eaton,[352] who described them under the name of lignilites and considered them organic in origin. They were designated epsomites by Vanuxem[353] and crystallites by Hunt.[354] Other names that have been used are "crow-feet," "toe-nails," suture joints, etc.

Origin

Early explanations of the origin of stylolites are more or less fanciful and of little value.[355] They were referred to an organic origin by some; considered as resulting from crystallization by others; still others assumed that a soft limestone ooze was exposed and developed shrinkage cracks, and columns resulted when this ooze was eroded by rain, pebbles and shells among other factors determining the location of columns; a few have ascribed the structure to escaping gas; and one student as late as 1858[356] thought that rising drops of petroleum might be the cause of origin, the clay at the tops of the stylolites being mistaken for petroleum. Of more reasonable character are the theories of later date, which refer the origin to pressure or solution. There has also been much difference of opinion as to the time of origin of

[349] Tarr, W. A., Stylolites in quartzite, Science, vol. 43, 1916, pp. 819–820.

[350] Freiesleben, J. C., Geognostische Arbeiten, Bd. 1, 1807.

[351] Klödin, F., Beiträge zur Mineral. u. Geol. Kenntniss der Mark Brandenburg, Bd. 1, 1828, p. 28.

[352] Eaton, A., Geol. Agric. Surv., Dist. adjoining Erie Canal, 1824, p. 134.

[353] Vanuxem, L., Geol. Surv. New York, 2d. Ann. Rept., 1838, p. 271.

[354] Hunt, T. S., Geol. Surv. Canada, Rept. Prog. from Commencement to 1863, 1863, p. 632.

[355] For the different advocates of the various theories see Stockdale, P. B., op. cit., 1922, pp. 21–24.

[356] Alberti, F. von., Über die Entstehung der Stylolithen, Jahresb. d. Verein f. Väterl.. Naturk. in Württemberg, 1858, p. 292.

stylolites, the advocates of the pressure theory considering them syngenetic and formed when the associated sediments were soft and unconsolidated, whereas the supporters of the solution theory hold that stylolites developed after consolidation and that the origin is epigenetic. Prominent advocates of the pressure theory are Marsh,[357] Gümbel and Dames,[358] and Rothpletz.[359]

Summaries of the important features of the various pressure theories are given by Stockdale (pp. 25–29). In general, these hold that the stylolites developed while the containing sediments were soft. In places on the surface of sediments destined to contain stylolites there were deposited shells and pebbles, or parts of the surface became locally cemented. As this surface became covered with overlying sediments, the shells, pebbles, etc. protected the muds immediately below, but there was settling around them and thus the stylolites developed. The rarity of any capping to the column other than clay, the undisturbed condition of laminæ surrounding columns, the penetration of one stylolite seam by another, the occurrence of stylolite seams along faults, the vertical positions of stylolites on inclined bedding planes, and the complete penetration of fossils by columns make it certain that the structures are not due to pressure alone. Theories referring stylolites to pressure alone are therefore obsolete, although it is still believed that pressure is a factor in stylolite formation.

The prevailing view with respect to stylolite formation is that they are directly due to solution, but that pressure differentially applied is an aiding factor. The solution theory is comparatively young, having been first suggested in 1895 by Fuchs.[360] Wagner[361] in his great work on stylolites appealed to this explanation, Gordon[362] was also of this opinion, and Stockdale[363] has marshalled a great deal of evidence for its support.

The solution theory explains stylolites as due to the removal of a part of the material on opposite sides of a parting plane, whether this plane is due to bedding, fracture, or some other cause. The pressure of the overburden is thought to be a factor, this pressure having differential application

[357] Marsh, O. C., On the origin of the so-called lignilites or epsomites, Proc. Am. Assoc. Adv. Sci., vol. 16, 1867, pp. 135–143.

[358] Gümbel, C. W. von, and Dames, W., Über die Bildung der Stylolithen etc., Zeits. d. deut. geol. Gesell., vol. 34, 1882; pp. 642–648; Über die Natur und Entstehungsweise der Stylolithen, ibid., vol. 40, 1888, pp. 187–188.

[359] Rothpletz, A., Über eigentümliche Deformation jurassischer Ammoniten durch Drucksuturen und deren Beziehung zu den Stylolithen, Sitz. d. k. bayr. Akad. d. Wiss., Math.-Phys. Kl., Bd. 30, Heft 2, 1900, pp. 3–32.

[360] Fuchs, T., op. cit., 1894.

[361] Wagner, G., op. cit., 1913.

[362] Gordon, C. H., op. cit., 1918.

[363] Stockdale, P. B., op. cit., 1922.

along the parting plane. The stylolite seams develop along these parting planes where there are differences in solubility and where there are also differences of pressure. The parts which are more soluble are removed. This shifts the points of contact along the parting planes and concentrates pressure at the places of previous solution. This in turn increases solution. The result is that the stylolites grow by removal of the material ahead of each column, the insoluble residue of the rock removed remaining as a cap and as a film over the column's sides.

The solution theory is supported by many facts, among which are: the distribution of stylolite seams, the dark clay cappings with composition like that of the insoluble residue of the adjacent rock, the penetration of an older stylolite seam by a younger, the penetration of fossils by stylolite columns and the total disappearance of the parts removed, and the sharp and undeflected ending of lamination planes and other structural features at stylolite columns. Stockdale[364] has shown that the thickness of the clay cap is in direct proportion to the height of the column and in inverse proportion to the purity of the limestone, thus essentially proving that the clay originated through solution of the limestone. That solution is extremely active along some parting planes has also been shown by Stockdale's[365] studies relating to this problem. He finds that many clay partings in the Salem limestone of Indiana have nearly the same composition in insoluble materials as does the adjacent limestone, and he considers that this clay in many instances resulted from solution of the overlying or underlying limestones, or both, no stylolites being formed when solution is not differential. It is probable that the various stages of stylolite formation are possible of demonstration in the laboratory.

The solution theory thus rests upon differential solution, which in turn is determined by differences in solubility of the rocks enclosing the parting plane and differential pressures applied to these rocks along this parting plane. Time is a factor in determining heights of columns, but it does not follow that the highest columns were the longest in forming.

The occurrence of stylolites in quartzite and shale is difficult to explain under the solution theory, and possibly other as yet unknown factors may form structures similar to the stylolites of limestones and dolomites. It is possible, however, that solution is the explanation for stylolites in quartzites, but it seems improbable that stylolites in shale could have been so formed.[366]

[364] Stockdale, P. B., op. cit., pp. 83–85.

[365] Stockdale, P. B., The stratigraphic significance of solution in rocks, Jour. Geol., vol. 34, 1926, pp. 399–414.

[366] Other important papers treating stylolites are: Hopkins, T. C., Stylolites, Am. Jour.,

CONTEMPORANEOUS DEFORMATION OF UNCONSOLIDATED SEDIMENTS

Deformation as here considered relates to surface movement of materials and not to movement of the crust. Named in the order of their probable importance, the different ways in which such deformation occurs are as follows:

Sliding (gliding)
Compacting
Lateral movement through pressure of overlying sediments
Thrust of surface agencies
Recrystallization
Removal of material by mining, solution, etc.

Deformation Resulting from Sliding

Sliding takes place in sediments for which support is inadequate and is defined as a downward movement of material with some degree of mobility over a plane built on material of much less mobility, the mobility being due to the nature of the composing material and its position, or to the presence of water. Inadequacy of support may be due to steepness of slope on which sediments are deposited, excessive local deposition, and removal of support through erosion of adjacent deposits, withdrawal of water, or melting of ice. It may take place either above or under water.[367]

Sediments settling on slopes with inclinations steeper than their angles of repose are certain to slide. There is much sliding on slopes the inclinations of which exceed 10° to 15°, and it is known to have taken place at inclinations as low as 2°31′.[368] Extensive areas of the sites of deposition have slopes of sufficient steepness to permit sliding. About volcanic islands and coral islands and reefs inclinations of 20° or more are common, and submarine fault slopes give far greater inclinations. On the eastern slope of the Bahamas the 2000-fathom depth is about 14 miles from land, giving an average inclination of nearly 16°, and Brownson[369] found depths exceeding 1900 fathoms 2½ miles from land, the inclination thus being 56.5°. The average value of the submarine slope for the 238 miles of the California coast between Point Conception and Point Descanso is 13.7°.[370]

Sci., vol. 4, 1897, pp. 142–144; Sorby, H. C., On the application of quantitative methods to the study of the structure and history of rocks, Quart. Jour. Geol. Soc., vol. 64, 1908, pp. 224–226.

367 Heim, A., Über rezente und fossile subaquatische Rutschungen und deren lithologische Bedeutung, Neues Jahrb. f. Min., Bd. 2, 1908, pp. 136–157.

368 Grabau, A. W., Principles of stratigraphy, 1913, p. 780.

369 Agassiz, A., Three cruises of the "Blake," vol. 1, 1888, p. 97.

370 Lawson, A. C., The continental shelf off the coast of California, Bull. Nat. Research Council, vol. 8, no. 44, 1924, p. 12.

Sliding brings sediments of shallow waters into deeper waters, where they become interstratified with the sediments of the latter. Such may have been the origin of the sands dredged in the South Atlantic from depths of 4000 to 4200 fathoms, a possibility suggested by the place of occurrence, although it has also been suggested that they arrived there through sinking of the bottom.[371]

The rapid deposition which locally obtains on the fronts of deltas creates slopes of high inclination, particularly in the smaller and less agitated bodies of water, and not uncommonly these slopes are of sufficient steepness to permit sliding. During the flood season of streams, sediments are deposited above normal water level. As the waters fall, support is removed and sliding may occur.

Subaqueous erosion of sediments is very common, particularly in streams. In the Missouri River in the vicinity of Nebraska City there are places where the bottom is thought to be scoured out to depths of 70 to 90 feet,[372] and at Omaha the sediments are removed at each flood season to bed rock, there about 40 feet below the bottom of the channel.[373] Similar scour probably occurs on sea bottoms, with sliding of marginal deposits into the depressions.

Glacial deposits not uncommonly are held up by ice against or over which they have been deposited. As the ice melts away, slumping takes place, with possible deformation of stratification.

Examples of recent subaqueous sliding of sediments are not uncommon, and data relating to many have been brought together by Heim.[374]

A slide in Lake Zuger, Switzerland, began March, 1435, and continued from time to time until July, 1887. The sliding material consisted of the sandy muds of a delta deposit which had been built in the lake when the latter stood at a higher level. The movement was initiated beneath the water and migrated landward through the removing of support on the lakeward side, ultimately forming a slide which was 1 to 12 meters thick, 250 meters wide, and extended lakeward for 1200 meters and 45 meters below lake level. The most pronounced movement took place over a slope with inclination of 2°31′, the average inclination of the surface on which the sliding occurred being 3°26′. The materials of the slide were brecciated, overfolded, and thrustfaulted, giving excessive thickness and overturning of beds.

A slide on the southern shore of Lake Zurich, Switzerland, involved sand,

[371] Philippi, E., Über das Problem der Schichtung, Zeits. d. deut. geol. Gesell., Bd. 60, Aufsätze, 1908, p. 366; Hahn, F. F., Neues Jahrb. f. Min., Beil.-Bd. 36, 1913, p. 13.

[372] Cooley, L. E., Rept. U. S. Engineers for 1879, pt. 2, pp. 1067–1073 (1071).

[373] Todd, J. E., Bull. 158, U. S. Geol. Surv., 1889, p. 15.

[374] Heim, A., op. cit., 1908, p. 136.

gravel, and clay underlain by soft clays, these in turn underlain by sands and marls of the Tertiary Molasse. Movement began in February, 1875, and continued to October, 1877. It appears to have been initiated through the squeezing out of the soft clays and continued until the rocks of the Molasse were bared for a distance of 300 meters. It began beneath water and was transferred landward, the slope on which the slide took place ranging in inclination from 15° to 17°. The material was carried lakeward to a depth of 125 meters.[375] Slides of similar magnitude and character have occurred in other Swiss lakes. Heim has described a very extensive slide which took place in 1895 near Odessa on the Black Sea. Others have been described from Sweden, and it is probable that many have escaped scientific record. Their occurrence in the geologic past was probably as common as it is today.

From the data collected it appears probable that the greater the volume undergoing movement, the smaller the slope on which movement can occur. The friction of the surface on which movement takes place tends to cause the materials behind to move over those in front, leading, in the lower portion of the sliding mass, to the development of asymmetrical or overturned folds, the steeper limb usually being down-slope. The upper portion of a slide is apt to have more open and symmetrical folds. In the lower portion of sliding sediments axial planes of folds incline into the slope at certain angles; they tend to be steeper in the upper portion, thus giving to the axial planes a radiate arrangement; but if the sliding material should encounter resistance above its base or pass to a reverse slope, the folds may have axial planes dipping down-slope, and more or less up-slope over-thrust may take place. Many folds are stretched on the axes, and some are apt to be faulted there. There usually is a considerable degree of mixing of materials along the bedding planes. Great complexity of structure may develop, depending upon the distribution of load, the character of the materials, the quantity of contained water, and the nature of the bordering conditions[376] (fig. 109).

Other features of importance resulting from sliding of sediments are as follows: (1) increase in number and thickness of the strata deposited in the deeper water, (2) decrease in number and thickness of the strata on that portion of the bottom from which the sediments slide, (3) superposition of older on younger beds, (4) displacement of facies, bringing sediment and fauna of shallow depth of water into the environment of greater depth, and (5) development of local unconformities. The diagram (fig. 109) illustrates these phenomena.

[375] Heim, A., op. cit., 1908, p. 136.

[376] de Terra, H., Structural features in gliding strata, Am. Jour. Sci., vol. 21, 1931, pp. 204–213.

The displacement of facies may lead to the assumption that the place of occurrence was in shallow water, and the close proximity to deposits of deeper water may seem to indicate oscillations of sea level. The local unconformity may suggest extremely erroneous views relating to the stratigraphy, paleogeography, and geologic history of the region and suggest the presence of this unconformity even in those exposures where it has not been seen.

Examples which have been interpreted as subaqueous slides are not uncommon in the geologic column. Ordovician strata exposed at Trenton Falls, New York, contain three zones of deformed strata lying between others which are not deformed. The deformed zones range in thickness up to 12

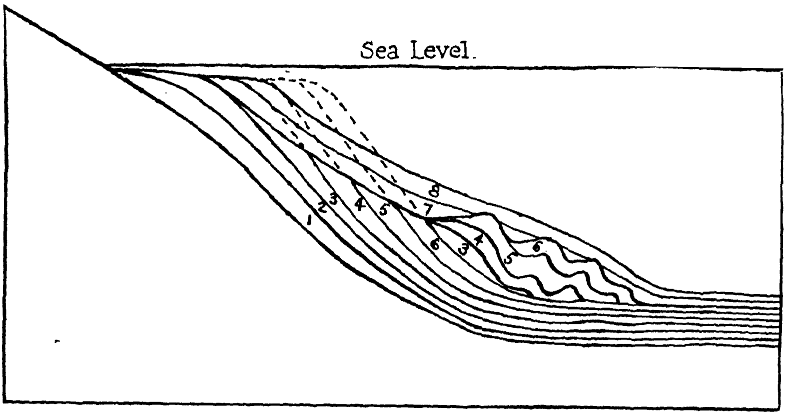


FIG. 109. DIAGRAM ILLUSTRATING EFFECTS OF SLIDING OR GLIDING OF SEDIMENTS

Parts of beds 3, 4, 5, and 6 have slid from their original position shown by the dashed lines. After the sliding, beds 7 and 8 were deposited. If the tops of the sliding sediments were within reach of wave and current action they would be eroded to some level conforming to the conditions. On the upper part of the slope an unconformity exists between 7 and all beds below. At the place of the sliding mass there is a structural break between 6 and the beds above, and apparently an unconformity between 7 and 6.

feet. The crumpled portions are not continuous and the same beds are not always involved, the crumpled strata in some places consisting of granular limestones and in others of calcareous shales.[377] Hahn suggested that the crumpling was related to tectonic movement; Miller[378] referred it to hard-rock faulting.

The Miocene lake marls of Oenigen, Germany, have a greatly crumpled

[377] Hahn, F. F., Untermeerische Gleitung bei Trenton Falls, etc., Neues Jahr. f. Min., Beil.-Bd. 36, 1913, pp. 1–41.

[378] Miller, W. J., Highly folded between non-folded strata at Trenton Falls, New York, Jour. Geol., vol. 16, 1908, pp. 428–433; Intraformational corrugated rocks, Ibid., vol. 30, 1922, pp. 587–610 (589).

layer lying between others which are not deformed. The limbs of some of the crumplings are notably thickened, and there is thinning on the axes. A splendid example of supposed sliding is the "krumme Lage" of the Solenhofen lithographic limestone. The Muschelkalk of the Main region contains strata showing structure which is thought to have arisen from sliding.[379] In the Devonian Cape Bon Ami limestone of the Gaspé Peninsula there is a

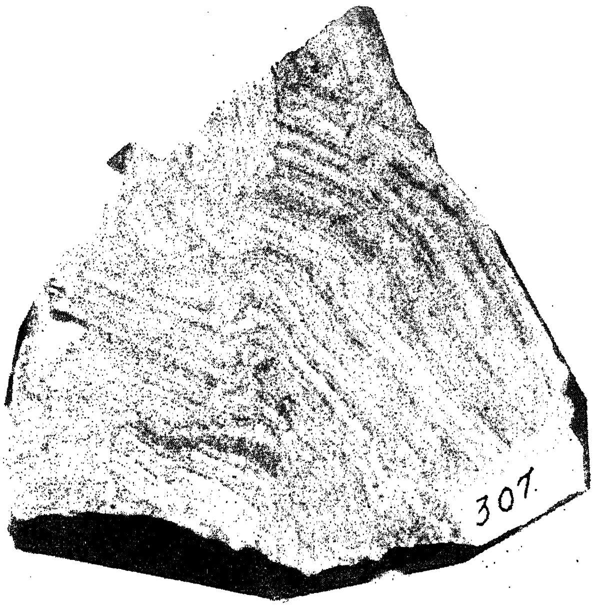


FIG. 110. CONTEMPORANEOUS DEFORMATION OF DOLOMITE

The specimen illustrated was collected by Doctor R. R. Shrock from the Kokomo limestones (Silurian) at Kokomo, Indiana. Traced laterally in the quarry wall the deformed strata pass into regularly bedded limestones. The deformed bodies have lenticular outlines with range in the vertical dimension up to 10 feet and in the horizontal up to 25 or 30 feet. According to Doctor Shrock the deformation took place while the materials were in soft condition. About one-half natural size.

strongly crumpled 7-foot zone composed of thin layers of limestone interstratified with calcareous shale. Many of the thin beds are broken into fragments.[380] Rothpletz[381] has described folded layers between unfolded

[379] Reis, O. M., Beobachtung über Schichtenfolge, Geogn. Jahresh., München, Bd. 22, 1909 (1910), pp. 1–285, pls. 1–11. This paper describes many occurrences of sliding.

[380] Logan, W. E., Geology of Canada, 1863, p. 392, fig. 425.

[381] Rothpletz, A., Meine Beobactungen über den Sparagmit und Birikalk am Mjösen in Norwegen. Sitz., K.-bayr. Akad. der Wiss., Math.-Natur. Kl., Bd. 15, 1910.

ones in the Biri limestone of Mjösen which may have originated through sliding. Similarly folded beds occur in three zones in the Anticosti Becscie formation in its exposures to the west of Fox Bay on the north side of the island. The involved beds are thin fine-grained limestones. The Casper sandstones of Wyoming (Pennsylvanian) "are locally crumpled into folds the axes of which are oriented in various directions and have various inclinations," the folds ranging from minute wrinkles to others with amplitude of 25 feet. Erosion planes cutting across the folded beds prove contemporaneous deformation, and the position of the folds in troughs due to scouring leads to the view that gliding was responsible.[382] Beautifully crumpled and brecciated strata are present in the Kokomo limestones of northern Indiana under such conditions that subaqueous sliding apparently must be responsible for their development (fig. 110).[383] Other examples are given by Miller[384] and Brown.[385]

If sliding sediments contain pebbles, these tilt in various directions, resulting in an edgewise conglomerate. Such conglomerates are common in one formation of the Cambrian sandstones of western Wisconsin and in Cambrian and Ordovician limestones of the Appalachian region. A conglomerate of this character in the lower part of the Pico formation of California has beds ranging in thickness from less than a foot to more than 20 feet. The pebbles show no assortment and have extremely random disposition. Cartwright states that gravity flows such as occur at present on the cliffed coast of California account for this type of conglomerate.[386] Conglomerates of this character may also develop in other ways, and it is not safe to assume a slide from their occurrence.

Deformation Arising from Compaction

Deformation caused by compaction of sediments may be grouped into two types, as follows: (1) settling of a coral reef through compaction and flow of underlying sediments, and (2) settling of sediments around a coral reef, a buried hill, or other rigid body. Compacting is important in clays, but probably not of great significance in sandstones and limestones. It is produced by closer spacing of particles and expulsion of water, and the

[382] Knight, S. H., The Fountain and the Casper formations of the Laramie Basin, Univ. Wyoming Publ., Geol. vol. 1, 1929, pp. 74–78; de Terra, H., Structural features in gliding strata, Am. Jour. Sci., vol. 21, 1931, pp. 204–213.

[383] Cumings, E. R., and Shrock, R. R., The geology of the Silurian rocks of northern Indiana, Publ. no. 75, Div. Geol., Dept. Conservation Indiana, 1928, p. 119.

[384] Miller, W. J., op. cit., 1922, pp. 596–605.

[385] Brown, T. C., Notes on the origin of certain Paleozoic sediments, etc., Jour. Geol., vol. 21, 1913, pp. 232–250.

[386] Cartwright, L. D., jr., Sedimentation of the Pico formation in the Ventura Quadrangle, California, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 253–254.

decrease in volume may rarely exceed 75 per cent and commonly exceeds 40 to 50 per cent.[387]

A coral reef may rest on muds or marls. The reef mass increases in weight and compacts the sediments beneath it, or causes flow toward its margins, with the result that the marginal basal strata incline toward the reef. Illustrations are stated by Bather[388] to be not uncommon about some of the reefs of Gotland, and the condition may obtain about other coral reefs.

A coral reef, an elevation on a pre-existing surface, or a lens of sands undergoes little or no compaction (a little in the case of the sands), whereas the sediments over and around such features may be so affected, particularly if they are muds, of which the compaction may equal 50 per cent or more.[389] Moreover, sediments about such features usually have an initial inclination therefrom. This is increased by the compaction, so that the strata which pass over the reef or other object become strongly arched and dip away at angles which locally rise to 30° or more. Deposits about high places tend to thicken away therefrom, particularly if there is much agitation of the water, or if the surface of deposition is sufficiently steep to cause sliding. This gradually builds up the marginal areas, and ultimately the surface becomes level. However, further settling of the underlying materials warps this level surface, and this continues until the effect of the original elevation is lost through compaction and deposition. A structure of this origin has been termed a compaction fold by Nevin and Sherrill.[390] Compaction folds cover progressively greater areas upward from the physiographic or depositional irregularities to which they are due; the sedimentary units which

[387] See on water content of uncompacted muds, Shaw, E. W., The rôle and fate of connate water in oil and gas sands, Bull. 103, Am. Inst. Min. Met. Eng., 1915, p. 1451; Meinzer, O. E., The occurrence of ground water in the United States, Water Supply Paper 489, U. S. Geol. Surv., 1923, p. 8; Lee, C. H. and Ellis, A. J., Water Supply Paper 446, U. S. Geol. Surv., 1919, pp. 121–123; Hedberg, H. D., Bull. Am. Assoc. Pet. Geol., vol. 10, 1926, p. 1042: Trask, P. D., Compaction of sediments, Bull. Am. Assoc. Pet. Geol., vol. 15, 1931, pp. 271–276.

[388] Bather, F. A., Proc. Geologists' Assoc., vol. 25, pt. iii, 1914, pp. 225–228.

[389] Mehl, M. G., The influence of the differential compression on the attitude of bedded rock, Science, vol. 1, 1920, p. 520; Blackwelder, E., The origin of the central Kansas oil domes, Bull. Am. Assoc. Pet. Geol., vol. 4, 1920, pp. 89–94; Monnett, V. E., Possible origin of some structures of the Mid-Continent oil field, Econ. Geol., vol. 17, 1922, pp. 194–200; Powers, S., Reflected buried hills and their importance in petroleum geology, Ibid., vol. 17, 1922, pp. 233–259; Teas, L. P., Differential compacting the cause of certain Claiborne dips, Bull. Am. Assoc. Pet. Geol., vol. 7, 1923, pp. 370–378; Lewis, J. V., Fissility of shale and its relation to petroleum, Bull. Geol. Soc. Am., vol. 35, 1924, pp. 562–566; Rubey, W. W., and Bass, N. W., Bull. 10, pt. i, Geol. Surv. Kansas, 1925, pp. 72–86; Bauer, C. M., Oil and gas fields of the Texas Panhandle, Bull. Am. Assoc. Pet. Geol., vol. 10, 1926, p. 734; Nevin, C. M. and Sherrill, R. E., Studies in differential compaction, Ibid., vol. 13, 1929, pp. 1–22, 1396–1397; Hedberg, H. D., The effect of gravitational compaction on the structure of sedimentary rocks, Ibid., vol. 10, 1926, pp. 1035–1072; Athy, L. F., Density, porosity, and compaction of sedimentary rocks, Ibid., vol. 14, 1930, pp. 1–25.

[390] Op. cit., p. 15.

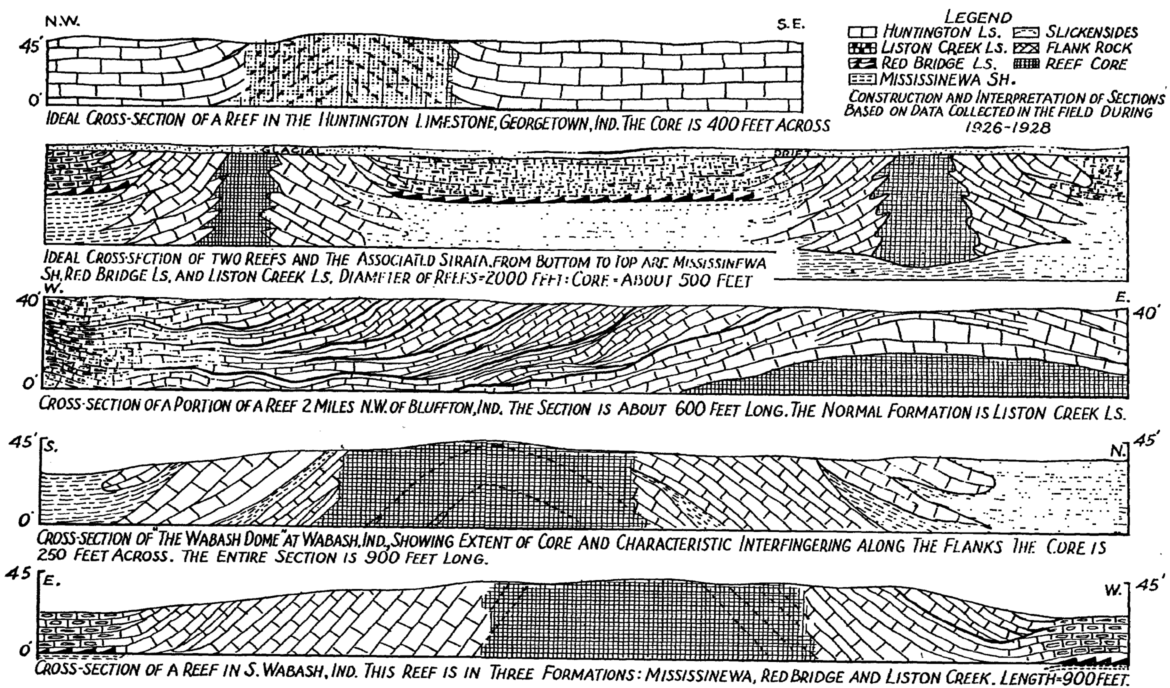


FIG. 111. CROSS SECTIONS OF CORAL REEFS OF INDIANA

After Cumings, E. R., and Shrock, R. R., The geology of the Silurian rocks of Indiana, Pub. no. 75, Dept. Conservation Indiana, Div. Geology, 1928, p. 146.

surround and cover these initial irregularities thicken outward therefrom, and dips increase with depth. Compaction folds should also show a general absence of system in distribution. It is to be noted, however, that not all of the "folding" is a result of compaction, but that the initial irregularity may give a warped bedding that is largely the result of deposition.

Steep dips about coral reefs are characteristic and are excellently shown about the Silurian reefs of Gotland, Anticosti, eastern Wisconsin, northern Indiana, and elsewhere. In the Shoonmaker quary, near Wauwatosa, Wisconsin, dips range to 54°, and dips around 30° are common.[391] In the reefs of Indiana dips range to 65°[392] (fig. 111). Dips in Gotland and Anticosti reefs are usually not more than 10°, but the "folding" is conspicuous because of excellent exposure in the seacoast cliffs. Coral reefs are likely to be characterized by steep slopes, and thus steep dips should be common. Langenbeck[393] notes slopes ranging to 90° or more, and Mayor states that the slopes of Tutuila range to 70° or more.[394]

Some of the domes and anticlines of Kansas and Oklahoma seem to be due to compaction of sediments around buried hills or sand lenses in the strata involved,[395] and Monnett found that in the Garber pool of Oklahoma a correspondence exists between the high parts of the structure and the thickness of a sandstone in the section.

Average surfaces of deposition are undulating,[396] and the undulations of successive sites of deposition are not necessarily parallel, and differential compacting modifies original positions. The results are that doming is almost certain to develop over little compactible materials, and the domes of one horizon are not necessarily in the same places in overlying and underlying horizons.

Lateral Movement from Pressure of Overlying Sediments

As sediments accumulate, the burden on those previously deposited increases, and if the overburden is differential, the muds in the section tend to move toward the places of least pressure. Experiments have shown that the flowing sediments thicken beneath the places of least pressure and thin

[391] Grabau, A. W., Principles of stratigraphy, 1913, p. 419.

[392] Cumings, E. R., and Shrock, R. R., The geology of the Silurian rocks of northern Indiana, Publ. No. 75, Dept. Conservation Indiana, 1928, pp. 138–156.

[393] Langenbeck, R., Die Theorien über die Entstehung der Koralleninseln und Korallenriffe und ihre Bedeutung für geophysische Fragen, Leipzig, 1890; Die neueren Forschungen über Korallenriffe, Hettsners Geogr. Zeits., 3. Jahrg., 1897, pp. 514–581.

[394] Mayor, A. G., Structure and ecology of Samoan reefs, Carnegie Inst. of Washington, vol. 19, 1924, pp. 1–25.

[395] See Blackwelder, Mehl, Powers, Bauer, op. cit.

[396] Shaw, E. W., Bull. Geol. Soc. Am., vol. 31, 1920, pp. 124–125.

beneath the greatest overburden, and that much crumpling results.[397] If the mud breaks through to the surface, collapse of the surface materials may take place. It has been suggested that the mud lumps at the mouth of the Mississippi owe their origin to the pressure of the sediments accumulating over the subaerial parts of the delta,[398] and that soft muds beneath the delta are being squeezed gulfward to break through at places of little resistance of the overburden. What actually takes place is not known, but figure 111 suggests the possibilities. It seems probable that similar phenomena are likely near the delta front where the fine-textured bottomset materials become overlain by the coarser sediments of the foreset beds.

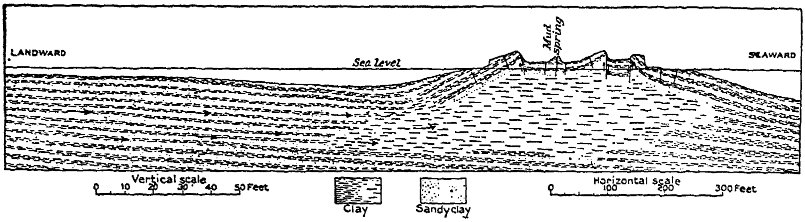


FIG. 112. PARTLY HYPOTHETICAL SECTION OF A MUDLUMP

This diagram of the eighth mudlump southeast of Pass a loutre Lighthouse, Mississippi Delta, shows the great clay body in the interior of the lump, the deformed clay and sandy clay strata above and on the sides, and the undeformed similar strata marginal to the lump. The arrows indicate the direction of supposed flowage of the clay from the landward side and the corresponding thinning of the clay beds on that side. The central part of this lump seems to have settled, but the central part of other lumps is known to have been raised. After E. W. Shaw, U. S. Geol. Surv.

Thrust of Surface Agencies

The thrusts may arise from glacial ice, grounding of floe ice and icebergs, lake ice, and sliding masses of earth or rock.

About the margins of glaciers the deposits are commonly unstratified, but in advance of these, and to some extent incorporated with them, are deposits which are stratified. Any advance of a glacier disturbs this material, leading to its brecciation, faulting, and folding. To the extent that the material is unstratified, no structural effect is produced, but in stratified material deformation results. It is thought that brecciation will be nearest the ice, succeeded outward by a zone of thrust faulting and overturned folds, and beyond this by a zone of low and gentle folding.[399]

[397] Kindle, E. M., Deformation of unconsolidated beds in Nova Scotia and southern Ontario, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 323–334.

[398] Shaw, E. W., The mud lumps at the mouths of the Mississippi, Prof. Paper 85–B, U. S. Geol. Surv., 1913, pp. 11–27.

[399] Case, E. C., Experiments in ice motion, Jour. Geol., vol. 3, 1895, pp. 918–934; Sollas, W. J., An experiment to illustrate the mode of flow of a viscous fluid, Quart. Jour. Geol.

Glaciers may also deform strata over which they move or against which they may collide. Soft strata at Gay Head on Martha's Vineyard and Clay Head on Block Island which have been overthrust and folded have been referred to the push of glacial ice.[400] Intense local deformation of Cretaceous strata in the Mud Buttes and Tit Hills of Alberta (fig. 113) has been referred to the pressure of the Pleistocene ice sheet by Hopkins[401] and Slater.[402] Similar deformation has been described from England and Denmark,[403] and many undescribed occurrences probably exist.

The grounding of floating ice disturbs the bottom materials, removes some of them, may produce deformation in the sediments beneath those removed, and folds and faults the surface materials around the front of the moving ice. Some of the folds are likely to be overturned, and most of the

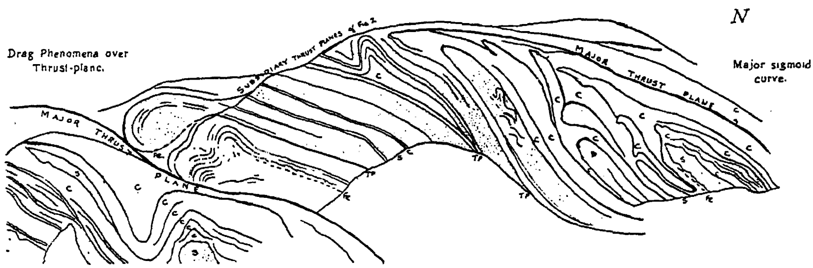


FIG. 113. A PARTIAL SECTION ACROSS THE MUD BUTTES OF ALBERTA

The dotted areas indicate sand, the white clay. The thrust planes are the heavy black lines. The thrust, caused by the advance of the Pleistocene glacier, came from the north. This is a part of the section given by Slater, G., in Bull. Geol. Soc. Am., vol. 38, 1927, opposite p. 724. Covers between 350 and 400 feet.

faults are thrusts. The clays of glacial lakes not uncommonly show these effects, and such have beautiful development in some of the glacial clays of the Connecticut River Valley and the Permian Squantum tillite.[404] De-

Soc., vol. 51, 1895, pp. 361–368; Slater, G., Glacial tectonics as reflected in disturbed drift deposits, Proc. Geologists' Assoc., vol. 37, 1926, pp. 392–400; The disturbed glacial deposits in the neighborhood of Lønstrup, near Hjøvring, North Denmark, Proc. Roy. Soc. Edinburgh, vol. 55, 1927, pp. 303–315.

[400] Woodworth, J. B., Unconformities of Marthas Vineyard and Block Island, Bull. Geol. Soc. Am., vol. 8, 1897, pp. 197–212.

[401] Hopkins, O. B., Some structural features of the Plains area of Alberta caused by Pleistocene glaciation, Bull. Geol. Soc. Am., vol. 34, 1923, pp. 419–430.

[402] Slater, G., Structure of the Mud Buttes and Tit Hills in Alberta, Bull. Geol. Soc. Am., vol. 38, 1927, pp. 721–730.

[403] Slater, G., Studies of the drift deposits of the southwestern part of Suffolk, Proc. Geologists' Assoc., vol. 38, 1927, pp. 157–216; The structure of the disturbed deposits of Möens Klint, Denmark, Proc. Roy. Soc. Edinburgh, vol. 55, 1927, pp. 289–302.

[404] Sayles, R. W., Seasonal deposition of aqueo-glacial sediments, Mem. Mus. Comp. Zool., vol. 47, 1919, pp. 37–38; Lahee, F. H., Contemporaneous deformation, a criterion

formation from this cause should be present in considerable abundance in the shallow-water sediments of polar seas,[405] and they should be found in sediments deposited in marine and lake waters adjacent to the continental and other glaciers of past geologic periods.

Sliding masses of earth and rock transmit a thrust to the materials in front of them and produce a drag on the materials over which they move. Some deformation probably arises from this cause. The great slide at Turtle Mountain, British Columbia, could not have failed to deform any unconsolidated materials over which the sliding masses moved; the landslide on the Lièvre River, Quebec,[406] must have deformed the river sediments involved therein, and it is probable that the great landslides occurring in China in 1920 led to considerable deformation of the involved materials.[407]

The expansions and contractions of lake ice produce a thrust of the materials composing the shores and the shallow-water deposits to which the ice may freeze. Locally this expresses itself in folding and faulting. The effects decrease with distance from the shore.[408]

Deformation Due to Recrystallization

Deformation arising from crystallization and hydration is usually associated with gypsum or other evaporites, but it may be connected with the formation of concretions. The latter process is considered in another connection. Some of the deformative structures associated with salt deposits have been termed enterolithic.[409] They appear to have their best development among the mother-liquor salts and are very abundant in the Stassfurt salt deposits where kieserite layers have been changed to carnalite.[410]

Calcium sulphate deposited from solutions high in chloride and under arid conditions is thought to be generally in the anhydrous form. After

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for aqueo-glacial deformation, Jour. Geol., vol. 22, 1914, pp. 786–790; Salisbury, R. D., and Atwood, W. W., Bull. no. 5, Wisconsin Geol. and Nat. Hist. Surv., 1900, p. 120, pl. 38.

[405] Stockton, C. H., Arctic cruise of the U. S. S. "Thetis," Nat. Geog. Mag., vol. 2, 1890, p. 182.

[406] Ells, R. W., The recent landslide on the Lièvre River, Quebec, Ann. Rept. Geol. Surv. Canada, vol. 15, pt. AA, 1906, pp. 136A–139A.

[407] Close, U., and McCormick, E., Where the mountains walked, Nat. Geog. Mag., vol. 61, 1922, pp. 462–464.

[408] Buckley, E. R., Ice ramparts, Trans. Wisconsin Acad. Sci., vol. 13, 1901, pp. 141–162.

[409] Grabau, A. W., Geology of the non-metallic mineral deposits, vol. 1, Principles of salt deposition, 1920, p. 372; Principles of stratigraphy, 1913, pp. 757–759, 788. It is quite certain that not all enterolithic structures are due to recrystallization. It seems to be established that many of the evaporites flow under conditions of pressures of moderate magnitude, the salt domes probably being formed in this way, and enterolithic structure develops as a consequence.

[410] Everding, H., Deutschlands Kalibergbau, Festsch. zum 10ten. Allgemeinen d. Bergmannstage zu Eisenach, vol. 1, 1907, pp. 25–133.

FIG. 114. DEFORMED GYPSUM AND ANHYDRITE, HILLSBOROUGH, NOVA SCOTIA
This deformation is believed to have resulted from the change of anhydrite to gypsum. Photograph by Diemer, University of Wisconsin.

deposition and entrance into the zone of ground-water circulation, this changes to gypsum with an increase in volume of 30 to 50 per cent. Expansion of the beds involved is a necessary result, with folding and faulting as probable effects. Features which are believed to be the result of this process are beautifully shown in the gypsum quarries near Hillsborough, New Brunswick. The deformation commonly is in the nature of miniature geanticlines and geosynclines in which there may be layers independently folded and faulted throughout the larger structures. A geanticline or geosyncline may have a height or depth of 6 to 8 inches (fig. 114).

The gypsum-containing Permian strata of central Kansas are more or less greatly deformed. The larger structures seem best explained as due to solution, but the smaller ones are thought to owe their origin to the change of anhydrite to gypsum.

Some deformation probably develops from the change of gypsum to anhydrite and aragonite to calcite, but no occurrences of such deformation are known to the writer.

Deformation Due to Removal of Material by Mining, Solution, or Other Agencies

Some deformation of stratification arises from mining, but most of this takes place in consolidated rocks and thus is not the concern of sedimentation. Similar deformation may be consequent to the formation of limestone caves; little of this also relates to sedimentation. Solution, however, acting on such soluble substances as rock salt and gypsum may produce more or less deformation of soft sediments. The Permian strata of Harvey and some portions of adjacent counties of Kansas are greatly deformed, with anticlines and synclines ranging up to 150 feet wide and 20 feet vertical dimension. The deformation seems to be best developed where gypsum constitutes a considerable percentage of the thickness, but it is also present where no gypsum is visible. Much minor deformation is associated. The latter is referred to alteration of anhydrite to gypsum, and it may be that the larger deformation was so caused.

DIMENSIONS OF SEDIMENTARY UNITS

The areal distribution of sedimentary units varies with the type of sediment and the environment of deposition. In general, the coarsest sediments have the most limited distribution and the greatest variations in thickness. All strata and aggregates of strata are lenticular, either thinning to disappearance or grading laterally into other varieties of sediments through decrease of the major constituent and increase of a minor constituent. Large loads and rapid decreases in the competency and capacity of the trans-

porting agents lead to limited areal distribution. On the other hand, the longer the transportation, the smaller the load, the slower the deposition, and the finer the materials: the more extensive the units.

Strata of very rapid deposition are apt to thin rapidly in a sourceward direction; those of slow deposition thin more or less equally in all directions. So many variables, however, influence the result that it is difficult to generalize.

The deposits of alluvial fans and cones and of river flood plains, channels, and deltas usually exhibit great variation in colors, materials, and thickness within short distances. Thus, one may find mud, sand, and gravel distributed in lenses of a few feet and even a few inches in diameter, and from these dimensions they pass upward into lenses of more extensive distribution on alluvial fans of wide extent and low slope, the flood plains of large rivers, and the surfaces of great deltas. Excellent illustrations are present in the Fort Union formation of Montana and Wyoming, the Tertiary of Nebraska and Kansas, and the subaerial delta deposits of the Pennsylvanian of Oklahoma, Kansas, Indiana, and elsewhere. In these deposits one may observe coal lenses ranging from those too thin and of too limited areal distribution for mining, to others miles in extent, and from sand and clay lenses a few feet in diameter to others which may be followed for several miles.

Extremely variable dimensions of sedimentary units exist in the deposits of the littoral environment and over those shallow marine bottoms subjected to strong wave and current action. The latter requires that the shallow bottoms be not too extensive or too shallow; otherwise strong waves and currents are not likely to develop. Along the littoral there are places where the same variety of sediment prevails for miles; other parts of the same coast have changes in sediments every few feet. On the permanently submerged shallow bottoms the conditions are not greatly different. This is particularly conspicuous about coral reefs where the lagoon, the channels between the reefs, and the sea outside the reefs possess different varieties of sediments on their bottoms. With increasing distance from land there is greater stability, and sedimentary units have wider extent, but even here more or less lateral variation may be expected for many miles from the shore and to depths of a couple of hundred feet. The submarine physiography is a factor of great importance. A sea bottom like that in the Channel Islands region of California, with deep basins separated by ridges, has different varieties of sediments in the basins and on the ridges, sedimentary units of one variety in a basin passing laterally into a coarser variety on an adjacent ridge.[411] Even bottoms deeper than the profile of equilibrium also have

[411] Trask, P. D., Sedimentation in the Channel Islands region, Econ. Geol., vol. 26, 1931, pp. 24–43.

variation, as some portions are receiving sands and muds derived from higher parts of the bottom, and other parts are the sites of organic colonies whose deposits vary with the responsible organisms. The units may be small or large, but are more likely to be of considerable dimension. In the still deeper waters beyond the sites of large deposition of terrigenous materials the areal limits are determined by the organisms which inhabit these depths. In the very deep waters up to 15,000 feet there are variations arising from the type of calcareous ooze, and below that depth they depend upon whether the deposits are radiolarian or diatom ooze or red clay. Deep sea units probably have the most extensive areal distribution.

Thus, the general rule obtains that the deposits of most existing environments of sedimentation are variable in extent and character, and each stratum and each formation is a lens of larger or smaller dimension. Past deposits, as Shaw[412] has noted, are more or less interpreted as not showing this variation, and the question is raised as to whether this is a matter of error in correlation or an actual occurrence. Ulrich has argued that the existing variations are abnormal in the same respect that he considers the existing climatic and topographic conditions out of the ordinary, and that during other geologic periods the seas were so shallow and the shores so low that the variations as they now are shown would have been impossible of materialization. He hence argues for a wide extension of the sedimentary units of the Paleozoic epicontinental seas.[413] Kindle[414] has presented evidence against such interpretation, and it seems rather improbable that sedimentary units could often have had the distribution postulated by Ulrich. That the waters had successive competencies to carry muds and sands is good evidence that these sediments grade laterally into each other and into limestones. That some of the Paleozoic seas give rise to deposits of limited distribution is certain. Thus, in the Silurian of Gotland coral limestone grades into other limestones, shale, or limestone conglomerate; in the Upper Ordovician of the Island of Anticosti limestones on the south side of the island are represented by quartz sandstones on the north side, less than 35 miles distant; and in the Pennsylvanian of Kansas and Oklahoma the variations are locally so abundant that the strata of two oil wells less than a half mile apart may show altogether different sequences. Splendid illustrations of lateral variations of sediments are found in the Tertiary of Trinidad where in the Naparima region "the lateral variation in some directions is so rapid that the rock-types of one area differ completely from their equivalent types a few miles

[412] Shaw, E. W., Discussion, Bull. Geol. Soc. Am., vol. 31, 1920, p. 123.

[413] Ulrich, E. O., Revision of the Paleozoic systems, Bull. Geol. Soc. Am., vol. 22, 1911, pp. 318–320.

[414] Kindle, E. M., The stratigraphic relations of the Devonian shales of northern Ohio, Am. Jour. Sci., vol. 34, 1912, pp. 187–196.

away," and in one locality in a distance of 3 miles a "marl formation disappears and is replaced by clays." A formation known as the Williamsville clays changes in thickness from 40 to 200 feet in a distance of 5 miles; a marl formation increases in a distance of 2.5 miles from 50 to 1500 feet; and a green clay from 50 to 650 feet.[415] Remarkable variations in thickness are present in the Tertiary of the Pacific Coast.

The fact of variations in thickness may determine other increase and variation. Lime accumulations due to planktonic and pelagic agencies are made only on those bottoms not so deep and not so abundantly provided with carbon dioxide that the lime passes into solution and does not attain permanent deposition. Bottoms permitting lime deposition would be built up, whereas surrounding bottoms of greater depth or with waters of higher solvent properties for lime would receive no or limited lime deposits. With rising sea level there might result a large accumulation of calcareous sediments surrounded by insolubles deposited from suspension. Adams[416] has suggested that the margins of such calcareous irregularities would rise faster than the central area, and thus there would develop a basin on top of the high place. This is his explanation of the "high" forming the Yates pool of west Texas. The suggestion is interesting and no doubt has some application.

However, it is known that some sedimentary units have very great areal distribution. The Pennsylvanian sequence of the Mid-Continent region has units of essentially constant thickness and composed of limestone, shale, or coal that may be followed for hundreds of miles.[417] The Iatan limestone of Kansas has one bed in its upper part which with essentially uniform thickness and composition extends from the vicinity of Leavenworth, Kansas, southwestwardly beyond the Oklahoma line, a distance around 200 miles, and this distribution is equalled and even exceeded by other units in the sequence. Condra, Dunbar, and Moore state that some coal units only an inch or two thick are "traceable for more than 300 miles." In the Pennsylvanian of southwestern Indiana is a fine-grained dark limestone, locally known as the "Steel Band." This has been seen with approximately uniform characteristics over an area of fully 1500 square miles, and it certainly has greater extent. In the Richmond of the Anticosti section is a 3 to 6 inch bed of compact, fine-grained limestone which is known as the "Track

[415] Illing, V. C., Geology of the Naparima region of Trinidad, British West Indies, Quart. Jour. Geol. Soc., vol. 84, 1928, pp. 7, 37–40.

[416] Adams, J. E., Origin of oil and its reservoir in Yates Pool, Pecos County, Texas, Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 705–717.

[417] Condra, G. E., Dunbar, C. O., and Moore, R. C., Persistence of thin beds in the Pennsylvanian of the northern Mid Continent region, Abstract, Bull. Geol. Soc. Am., vol. 41, 1930, p. 104.

Bed" because of the occurrence on its upper surface of double rows of pits which have been interpreted as tracks. This bed is known to have an east-west distribution of 75 miles, with the certainty that it extends farther east than it has been seen and that it once had far greater westward extent. The Silurian of Gotland has a thin bed filled with the brachiopod, *Dayia navicula*, which has been traced across the width of the island. Many of these examples of extensive areal distribution are remarkable because of association with units of considerable lenticularity.

As already noted, many sedimentary units have great range in thickness from place to place. These variations are partly due to variations in the rate of deposition, but some variations must be referred to local and temporal failure of deposition and in some instances to erosion. Hunter[418] has shown that over an area of the bottom in Chesapeake Bay in the fifty-two year interval from 1848 to 1900 about 66 per cent received no deposits, 26 per cent received deposits, and 8 per cent underwent deepening and erosion. This means variations in thickness from place to place and hence lenticularity of beds.

Textures of Sediments

The textures of sedimentary rocks have a wide range and are intimately related to the characteristics of the materials deposited. To attempt their individual consideration would lead to such length that it is not considered justified. They may be grouped, with a few exceptions, in three classes: fragmental, crystalline, and oolitic. This does not include the textures of such sediments as coal.

FRAGMENTAL TEXTURES

Fragmental textures of sediments range from those found in clays and shales to those of sandstones and conglomerates. Limestones also very commonly have fragmental textures. The particles have a considerable range in dimension in the same specimen and a very wide one if all detritals are considered.

CRYSTALLINE TEXTURES

Crystalline textures are found in limestone, dolomite, gypsum, rock salt, and similar substances. Many sandstones have enlarged particles so that a crystalline texture is produced, and, although it is not visible to the eye, many shales in greater or less degree are finely crystalline. More or less crystalline material, however, may be expected in every sedimentary rock

[418] Hunter, J. F., Erosion and sedimentation in Chesapeake Bay around the mouth of Choptank River, Prof. Paper 90-B, U. S. Geol. Sur., 1914, p. 14.

except the coarse clastics. There is a wide range in the dimensions of the crystalline particles from those so small as to be invisible with an ordinary lens to others 6 to 12 mm. in diameter. The crystallization considered is that developed as a consequence of surface processes. Studies made of dolomites derived from a deep well at Spur, Texas,[419] showed an increase in the dimensions of crystals with depth, suggesting that in the crystallizing of the original materials of the sediments to form dolomite, complete growth was not acquired at the time of burial, and that enlargement continued after burial. Adverse to any view that depth of burial and time involved are functions controlling dimension is the occurrence at several levels in the Spur well of crystals of smaller dimension than those in overlying strata. That time is a factor of importance in growth seems certain, but it does not seem probable that depth has much influence. The occurrence is considered a coincidence.

OOLITES AND PISOLITES, AND OOLITIC AND PISOLITIC TEXTURES

Oolites are small rock particles of elliptical or spherical shapes with concentrically laminated structure. Rocks in which oolites occur in comparative abundance are said to have an oolitic texture. The maximum dimension of an oolite may be placed at about 2 mm. If the dimensions are greater, the particles are called pisolites and the containing rocks have pisolitic texture. Particles of dimensions similar to oolites and pisolites but with radiate and not concentric structure are designated spherulites. It is to be noted, however, that this latter term has also been applied to spherical aggregates without either radiate or concentric structure. Many oolites and pisolites have radiate structure in some or all of the laminations. This is notably the case in the Great Salt Lake oolites and in artificial oolites later to be described. Most oolites and pisolites have nuclei. These commonly are particles of quartz, feldspar, or other minerals, fragments of shells, or gas bubbles,[420] and oolites in some Mexican lakes are said to have insect eggs as nuclei.[421]

There are many particles formed or deposited in sedimentary environments which have spheroidal shapes but are without concentric or radiate structure. Among these are greenalite, common in the Pre-Cambrian of the Lake Superior region; glauconite, abundant in the marine sediments of many systems; and the coprolites, now abundant over many parts of the

[419] Udden, J. A., The deep boring at Spur, Bull. 28, Univ. Texas, Sci. Ser., 1914, p. 55.

[420] Vaughan, T. Wayland, Florida Studies, Carnegie Inst. of Washington, Year Book No. 11, 1913, pp. 157–158; also earlier suggested by Linck, op. cit.

[421] Virlet d'Aoust, Théodore, Sur des œufs d'insectes servant à l'alimentation de l'homme et donnant lieu à la formation d'oolithes dans des calcaires lacustres, au Mexique, Paris, Compt. Rend., vol. 45, 1857, pp. 865–868.

sea floor and also identified in some ancient sediments. These are not oolites, pisolites, or spherulites.

Oolites and pisolites may be composed of hematite, limonite, pyrite, bauxite, dolomite, calcite, aragonite, flint or chert, clay, barite, phosphate, and siderite. Limestones, dolomites, hematite, limonite, phosphate, bauxite, and flint or chert are the rocks most commonly possessing oolitic texture. In many of the occurrences it has been suggested that the oolites were originally calcite or aragonite and were replaced by other substances. This suggestion cannot be generally sustained, and it seems certain that oolites of substances other than calcite or aragonite may develop directly.

Oolites and pisolites are generally spheroidal or ellipsoidal, although depressions may be present on their surfaces due to contact of one against another. Lacroix,[422] Shrock,[423] and Rodolico[424] have described polyhedral pisolites. The pisolites described by Shrock were found in a glacial cobble, and the terrane of origin is not known. Lacroix' examples were collected in Madagascar and in Algeria. Rodolico's specimens were collected in Italy. Shrock's pisolites have concentric and radiate structure with bands of iron oxide forming some of the concentric laminæ. The interior laminations are spherical. The polyhedral shapes are probably to be assigned to interference with each other as the pisolites grew.

The problems of oolites and pisolites are considered from the two points of view of the substances of which these structures are composed and something with respect to their distribution, and the facts, experiments, and theories relating to their origin.

Materials of Which Oolites and Pisolites Are Composed

Oolites and Pisolites of Silica. The basal part of the Oneota dolomite of the upper Mississippi Valley contains nodules of oolitic chert distributed through a thickness of about 30 feet. The surrounding dolomite is also oolitic, and it is obvious that the silica oolites developed through replacement of other materials. Silica oolites in Center County, Pennsylvania, were assigned by Wieland to hot-spring origin,[425] but Brown[426] and

[422] Lacroix, A., Sur la ctypéite, etc., Compt. Rend. vol. 126, 1898, p. 601; Minéralogie de la France, vol. 3, 1901, p. 733; Minéralogie de Madagascar, vol. 1, 1922, p. 288.

[423] Shrock, R. R., Polyhedral pisolites, Am. Jour. Sci., vol. 19, 1930, pp. 368-372.

[424] Rodolico, F., Pisoliti poliedrici di magnisite e di dolomite, Rendiconte della R. Accademia Nazionale dei Lincei, vol. 12, ser. 6, 1930, pp. 457–460.

[425] Wieland, G. R., Eopaleozoic hot springs and the origin of the Pennsylvania siliceous oölite, Am. Jour. Sci., vol. 4, 1897, pp. 262–264; Further notes on Ozarkian sea-weeds and oölites, Bull. Am. Mus. Nat. Hist., vol. 33, 1914, pp. 248–255; Ziegler, V., The siliceous oölites of central Pennsylvania, Am. Jour. Sci., vol. 34, 1912, pp. 113–127.

[426] Brown, T. C., Origin of oolites and the oolitic texture in rocks, Bull. Geol. Soc. Am., vol. 25, 1914, pp. 745–780, pls. 26–28.

Moore[427] considered these same oolites to have been originally composed of calcium carbonate which was later replaced by silica. Silica oolites occur in the Pre-Cambrian of the Lake Superior region, and some of these have some laminæ composed of iron carbonate. Takimoto has described spherulitic hyalite from hot springs of Ugo Province of Japan,[428] and Jimbo[429] from another province. These Japanese occurrences, however, do not appear to be replacements. Tarr[430] found siliceous oolites of laminated structure in red, yellow, and green shales of the Red Beds of the Wind River Mountains near Lander, Wyoming. They are of two dimensions, the larger with diameters around 0.6 mm. and the smaller with diameters of 0.1 to 0.2 mm. Some of the oolites contain sand grains which were enclosed as the particles were growing. The oolites are not confined to definite laminations in the shale, but are scattered throughout and in no way disturb the shale laminæ. The shales also contain particles of calcite. If two oolites interfered while growing, a regular contact was preserved, and in some instances large oolites grew around smaller ones. Tarr considers that the relations prove the oolites were always siliceous, formed in muddy waters and were deposited contemporaneously with the surrounding materials. He thinks that the silica was precipitated as a colloidal gel and that the union of the gel particles formed the oolites.

It is not unlikely that oolites of silica occur in every geologic system, but they appear to be more abundant in the earlier ones. Many are certainly replacements, but it seems probable that some may have been precipitated directly.

Oolites and Pisolites of Hematite and Limonite. Particles with oolitic structure form to some extent in the iron oxides which are being deposited on the bottoms of some Swedish and Finnish lakes and certain lakes of other regions.[431] These are certainly not replacements. Oolitic hematite and limonite are present in the Lower Cambrian on the Strait of Belle Isle, the Ordovician of Bell Island, Newfoundland, the Upper Ordovician of Wisconsin, the Clinton of the Appalachian region, the Jurassic Minette ores of Luxemburg and Lorraine, etc. The oolites have been variously considered to have been iron oxides from the beginning, replacements of calcite

[427] Moore, E. S., Siliceous oolites and other concretionary structures in the vicinity of State College, Pennsylvania, Jour. Geol., vol. 20, 1912, p. 266.

[428] Takimoto, T., The siliceous oolite of Sankyo, Ugo Province, Beiträge zur Min. von Japan, no. 2, 1906, pp. 60–61, quoted from Neues Jahrb. für Min., etc., vol. 1, 1907, p. 197.

[429] Jimbo, K., The siliceous oolite of Toteyama, Etchu Province, Beiträge zur Min., Japan, 1905, pp. 11–75. Abstract in Zeits. f. Chemie und Industrie der Kolloide, vol. 4, 1909, p. 287.

[430] Tarr, W. A., Oolites in shale and their origin, Bull. Geol. Soc. Am., vol. 29, 1918, pp. 587–600.

[431] Beck, R., The nature of ore deposits, Transl. by Weed, W. H., 1909, p. 101.

oolites, alterations of other iron-bearing minerals, and in the case of the Clinton ores Wieland[432] suggested that these were due to the alternate precipitation of silica and hematite about nuclei, suggested by the fact that when the iron oxide is dissolved concentric tests of silica remain. Some of the Clinton oolites are green and are composed of alternate laminæ of differently colored chloritic and siliceous matter surrounding grains of quartz. The cherts of the Lake Superior region contain oolites or concretions which are composed of concentric bands of chert, chert and iron oxide,[433] or of red jaspery and black graphitic material.[434] According to Aldrich,[435] some of the chert oolites have carbonate cleavage planes, strongly suggesting that they are replacements of carbonate by silica.

Van Werveke[436] expressed the opinion that the Minette oolites were deposited as carbonate, silicate, sulphide, and possibly as ferric hydrate. Pisolitic or "shot" particles are present in the lateritic iron ores of Cuba[437] and in the laterites of many regions. They are produced in the formation of the laterite. Some of them contain magnetite, also a product of decomposition.

Oolites and Pisolites of Phosphate. Oolites and pisolites of phosphate are present in Montana, Idaho, Utah, and Wyoming in strata of late Carboniferous age. Mansfield[438] considered that they have been deposited as aragonite which was later phosphoritized by impregnation with ammonium phosphate produced from bacterial decay of marine organisms. He considers this to have been done in shoal waters under conditions of warm and moderate temperature. Pardee[439] was of the opinion "that conditions especially favorable to the solution and retention of calcium carbonate by the sea water, but not hindering the ordinary precipitation of phosphate, existed for a considerable time," so that the oolites were composed of phosphate from the beginning. He considered that the waters were too cold to favor the abundant development of lime-secreting organisms, and this coldness favored a high retention of carbon dioxide which would lead to the solution of much of the lime that might be precipitated, so that the calcium

[432] Wieland, G. R., op. cit., 1914, pp. 253–254.

[433] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region, Mon. 52, U. S. Geol. Surv., 1911, p. 536, pls. 42 and 45.

[434] Gruner, J. W., The origin of sedimentary iron formations: The Biwabik formation of the Mesabi Range, Econ. Geol., vol. 17, 1922, p. 414.

[435] Aldrich, H. A., Personal communication.

[436] Van Werveke, L., Ueber die Zusammensetzung und Entstehung der Minetten, Reviewed Zeits. für Pract. Geol., 1901, pp. 496–503.

[437] Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, p. 37.

[438] Mansfield, G. R., Origin of the western phosphates of the United States, Am. Jour. Sci., vol. 46, 1918, p. 591.

[439] Pardee, J. T., The Garrison and Philipsburg phosphate fields, Montana, Bull. 640, U. S. Geol. Surv., 1917, pp. 226–227.

phosphate would acumulate in essentially pure form. The fact that many of the spherical particles have neither concentric nor laminated structures prevents these from being considered oolites, and hence their origin may not be related to the origin of the oolites. These particles are probably best interpreted as excremental or coprolitic in origin, and many of them seem to have functioned as nuclei around which were deposited concentric laminæ. Dimensions range from very small to pisolites 6 mm. in diameter.

Oolites and Pisolites of Bauxite. Oolites and pisolites of bauxite have been described by Mead[440] from Arkansas, and they appear to be common in bauxite deposits elsewhere. They range in dimension from microscopic to a maximum of about 25 mm. The Arkansas oolites and pisolites are residual products resulting from the surface weathering of "syenite by normal processes of rock decomposition."

Oolites and Pisolites of Barite. Oolites and pisolites of barite were obtained from wells in the Saratoga oil field, Texas. They were formed in the wells after the latter had been equipped, and it is quite certain that the oolites and pisolites had developed in the fluid—oil and water—in the wells, as their dimensions are such as to preclude passage into the wells through screens connecting with the penetrated sands. The fluid in the wells had a temperature of 125°F., and it contained some sulphuric acid, which may have been concerned in the formation. Diameters range from 1.25 to 5 mm. The color is a dirty white, and the shapes range from spherical to ovoid and disk shaped. The disk-shaped individuals have nuclei which seem to be pieces of pipe scale.[441] The structure is concentric, with the center of barite in more porous form than that surrounding. There is no evidence of replacement.[442]

Oolites of Siderite. Oolites of siderite appear to be rather rare. An example has been described by DeWalque[443] from the Belgian coal measures, the siderite having calcite and pyrite in association.

Oolites of Silicate. Grains of light green silicate are present in Devonian limestones of Bath County, Kentucky, the particles having maximum diameters of 0.07 mm.[444] The greenalite particles of the Lake Superior

[440] Mead, W. J., Occurrence and origin of the bauxite deposits of Arkansas, Econ. Geol., vol. 10, 1915, pp. 39–40.

[441] Barton, D. C., and Mason, S. L., Further notes on barite pisolites from the Batson and Saratoga oil fields, Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, pp. 1294–1295.

[442] Wuestner, H., Pisolitic barite, Jour. Cincinnati Soc. Nat. Hist., vol. 20, 1906, pp. 245–250; Moore, E. S., Oolitic and pisolitic barite from the Saratoga oil field, Texas, Bull. Geol. Soc. Am., vol. 25, 1914, pp. 77–79; Moore, E. S., Additional note on the oolitic and pisolitic barite from the Saratoga oil field, Texas, Science, vol. 46, 1917, p. 342; Suman, J., The Saratoga oil field, Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, p. 275.

[443] DeWalque, G., Ann. Soc. Géol. Belg., vol. 15, 1888, pp. lxxviii–lxxx.

[444] Bucher, W. H., On oolites and spherulites, Jour. Geol., vol. 26, 1918, pp. 598, 600.

country are spherical, but they do not have concentric or radial structure. The chamosite of the Minette ores of Europe is stated to be commonly in oolitic form. Bucher also has described oolitic texture present in a fire clay from the base of the Pottsville of eastern Kentucky, and he states that Tarr has noted a similar occurrence. Cady[445] gives a section of the St. Peter sandstone of Illinois in which he records the presence of a few inches of oolitic clay.

OOLITES OF PYRITE. Oolitic pyrite in lenticular but persistent beds is present in the Wabana iron ores of Bell Island, Newfoundland.[446] The oolites seem to be of syngenetic origin. Beds of a similar character are in the Devonian of Westphalia, where they average about 10 feet thick and are composed of pyrite and barite, the pyrite being oolitic only in part.[447] Bucher[448] tells of the occurrence of pyrite oolites in a black limestone of the upper Lias of northwest Germany, the oolites consisting of alternating layers of yellow pyrite and black calcium carbonate.

OOLITES AND PISOLITES OF CALCITE AND DOLOMITE. Most oolites and pisolites are composed of either calcite or dolomite, the latter thought to be secondary. The range in dimension is from microscopic to about 25 mm. Most ancient calcite and dolomite oolites are associated with marine strata, but Mansfield has described limestone pisolites from the non-marine Tertiary of southwestern Idaho. Whether these were formed in fresh- or salt-water bodies is not known. Oolites are now forming in Great Salt Lake, the Carlsbad Springs of Bohemia, the waters about Florida, the Red Sea, etc., and they are probably present in the rocks of every geologic system.

SUMMARY. The foregoing shows that oolites may be of residual origin, may develop in oil wells, may form in both fresh and salt water, but appear most commonly to have developed in a salt-water environment.

In studying oolites and pisolites it should be remembered that the particles after formation are of sand, granule, or pebble dimensions, and that they may be transported and deposited as and with those substances. Thus, oolites may be differentiated into those which were developed where they are found and those which underwent considerable transportation before final deposition. In the latter case they are the result of mechanical deposition and exhibit the structures of such in the presence of ripple mark and cross-lamination, and either feature may have been developed by wind or water. Deposition by wind is now occurring on the shores of Florida, Great

[445] Cady, G. H., Bull. 37, Geol. Surv. Illinois, 1919, p. 39.

[446] Hayes, A. O., Wabana iron ore of Newfoundland, Mem. 78, Geol. Surv. Canada, 1915, pp. 10, 15.

[447] Stelzner, A. W., and Bergeat, A., Die Erzlagerstätten, Bd. 1, 1904, pp. 339–342.

[448] Bucher, W. H., op. cit., p. 600.

Salt Lake, Red Sea, etc. Cross-laminated oolites are present in the Silurian of Gotland, the Pennsylvanian of Kansas, the Mississippian of Kentucky (fig. 115), etc. Some of these have the wedge-shaped cross-laminated units characteristic of wind deposition. A feature of such mechanically deposited oolites is the presence of small fossils which are usually the young of species normally larger. They are associated with the oolites for the same reason that the latter are there,—they are within the range of competency of the agents which transported the oolites. An occasional large shell may drift into a

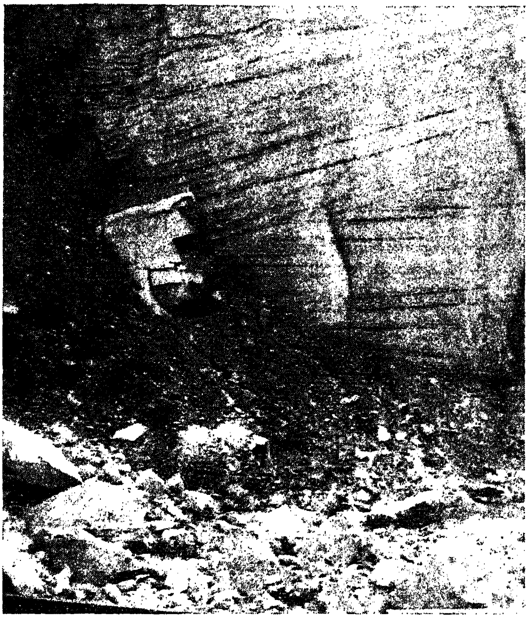


FIG. 115. CROSS-LAMINATED OOLITIC LIMESTONE

The foresets, or inclined beds, are fully 20 feet long. Exposure in Mississippian limestone in the Poplar Quarry, Carter County, Kentucky. Photograph by W. H. Twenhofel.

deposit of transported oolites, or it may have been grown at the place preceding or during their deposition. Mechanically transported oolites derived from preexisting formations seem to be rare, and it is not known that any exist, although such an origin has been postulated[449] for oolites in the Sylamore sandstone (Lower Mississippian) of Arkansas. It is more probable that these oolites were formed on the bottom or shores of Sylamore waters.

[449] Swartzlow, C. R., Pan-Am. Geologist, vol. 53, 1930, pp. 197–200.

Oolites which underwent no transportation after origin should not be found in cross-laminated sediments unless it is possible for them to develop therein, and they should be more or less uniformly embedded in the layers in which they occur.

Facts, Experiments, and Hypotheses Relating to the Origin of Oolites

There is little general agreement with respect to the ways in which oolites develop, probably due to the fact that their origins may be various and may result from several different combinations of conditions.

The pisolites of the Carlsbad Springs of Bohemia are said to develop through the deposition of calcium carbonate about various nuclei as the latter are suspended and rotated in the rising waters. The nuclei commonly consist of small particles of quartz and feldspar, and in some instances bubbles appear to have functioned.[450] Similar deposition around nuclei seems possible in any water saturated with lime carbonate, particularly at times of agitation when there is much release of carbon dioxide. Some of the oolites in the Gotland section may have originated in this way, as associated shells are often thickly coated with lime carbonate, although it is possible that algæ may have been the agents responsible for the deposition around the shells. Oolites of concentric structure with small particles of iron or iron oxide as nuclei developed in the hot-water coil of the writer's furnace. In this case the water was at high temperatures and in circulation, which at some times was rapid. The nuclei are supposed to have come from particles of rust detached from the pipes or from particles of iron left in the pipes at the time of their installation. The water entering the coil came from the Potsdam sandstone and was conspicuously hard. When first studied, the concentric laminæ of these oolites did not seem to have had radiate structure, although such was sought for. They have such structure at the present time.

An extremely interesting occurrence of oolites and pisolites is that described by Hess[451] from the Carlsbad Cave of New Mexico. These range in diameter from 1.5 to 25 or 30 mm. and are composed of calcite. Most are spherical; some are oval or of irregular shapes. Most are white, but impurities give some a yellowish color. Nuclei are calcite. The structure is concentric, and some laminæ have radial structure. These oolites form in little pools on the cave floor in which the water is agitated by drops falling from the roof. The agitation facilitates escape of carbon dioxide, leading

[450] Hochstetter, H. V., Karlsbad, seine geognostische Verhältnisse und seine Quellen, 1856.

[451] Hess, F. L., Oölites or cave pearls in the Carlsbad caverns, Proc. U. S. Nat. Mus., no. 2813, vol. 76, 1929, pp. 1–5, pls. 1–8.

to precipitation and deposition of calcium carbonate upon and around anything in the pools. It is postulated that the agitation also rotates the nuclei and the forming oolites and it is assumed that such rotation is necessary for oolite formation. The oolites seem to be built by deposition of calcium carbonate directly from solution. As pointed out by Hess, hail seems to form somewhat in the same way, except that in hail deposition may be directly from water vapor, and he states that nickel oolites form in the Mond process for obtaining nickel from its ores through direct precipitation from the gaseous state. Oolites which seem to have been formed under conditions somewhat similar to those described by Hess have also been found at four localities in Mexican mines except that rotation of the oolites during their formation seems precluded.[452]

Rothpletz[453] came to the conclusion that the oolites of Great Salt Lake developed through the agency of algæ belonging to the genera *Glœocapsa* and *Glœotheca*, the oolites forming in the slimy masses of the assembled organisms, and he asserted a similar origin for the oolites which have extensive development in some portions of the Red Sea.

The streams flowing into Great Salt Lake carry notable quantities of calcium carbonate in solution. The waters of the lake contain no calcium carbonate and only small quantities of calcium chloride and calcium sulphate. The lime on entering the lake probably is precipitated because of the inability of the strong brine to hold it in solution, and it may be that the precipitated material is in such state as to favor the formation of oolites. Wethered's[454] studies of the Jurassic oolites of England led him to the view that oolites are largely the result of the activities of filiform algæ, and he distinguished several species of *Girvanella* which he considered of importance in this respect. Kalkovski[455] has described oolites from the salt lakes of the Kalihari desert which he assigned to an algal origin, and Rothpletz[456] formulated the generalization that the "majority of the marine calcareous oolites with regular and radial zonal structure are of plant origin; the product of microscopically small algæ of low rank, capable of secreting lime carbonate." Some of the oolites studied by Rothpletz had vermiform and

[452] Davidson, S. C., and McKinstry, H. E., "Cave pearls," oolites, and isolated inclusions in veins, Econ. Geol., vol. 26, 1931, pp. 289–294.

[453] Rothpletz, A., On the formation of oölite, Bot. Centralb., Nr. 35, 1892, Transl. by Cragin, F. W., Am. Geol., vol. 10, 1892, pp. 279–282.

[454] Wethered, E., On the occurrence of Girvanella in oolitic rocks and remarks on oolitic structure, Quart. Jour. Geol. Soc., vol. 46, 1890, pp. 270–283; The formation of oolite, Ibid., vol. 51, 1895, pp. 196–209.

[455] Kalkovski, E., Die Verkieselung der Gesteine in der nördlichen Kalahari, Sitz. u. Abh. Gesell. 'Isis', Abh. pp. 55–107, 1901, 1902.

[456] Rothpletz, A., op. cit., 1892, pp. 265–268.

branching canals, for whose origin filiform algæ living in symbiosis with the lime-secreting types have been suggested. Van Tuyl[457] described oolites from the Ordovician of Iowa which contained "minute sinuous fibers" like those characteristic of "the *Girvanella* type of calcareous algæ." Bradley[458] in his earlier studies of the oolites in the Green River formation advanced the view that microscopic plants were concerned in their origin, but later abandoned this view.[459] The minute canals and "sinuous fibers" found in some oolites do not prove that algæ were concerned in their formation, as they may be due to algæ enclosed within a growing oolite, or they may have been later produced by minute boring organisms.

According to Linck,[460] whenever the quantity of calcium carbonate in sea water exceeds the limit of maximum solubility[461] for the conditions, it is precipitated as calcium carbonate in temperate, and as aragonite in tropical latitudes,[462] in either case without the formation of spherulites. If the precipitation of calcium carbonate arises from the reaction of sodium or ammonium carbonate on calcium sulphate, the product is always aragonite, which may have radiate or concentric structure, and in the latter case with or without the nucleus. Linck's approach was experimental, and he concluded that all oolites and pisolites are of inorganic chemical origin and that any organic matter included is merely incidental, and instead of the oolites being secreted by algæ they served as places of attachment for the latter. He considered the algous rods of Rothpletz as minute crystals of aragonite having no connection with algæ.

Following his investigations of the bottom muds of the waters about the Bahamas and Florida, Vaughan expressed the opinion that the deposition of much of the lime mud of these bottoms was due to bacteria, and he stated that some of the precipitated lime was in the form of aggregates of aragonite needles which by growth might become oolites.[463] The aggregates observed

[457] Van Tuyl, F. M., Science, vol. 43, 1916, p. 171; A contribution to the oolite problem, Jour. Geol., vol. 24, 1916, pp. 792–797.

[458] Bradley, W. H., Shore phases of the Green River formation in northern Sweetwater County, Wyoming, Prof. Paper 140–D, U. S. Geol. Surv., 1926, p. 126.

[459] Bradley, W. H., Algæ reefs and oolites of the Green River formation, Prof. Paper, 154-G, U. S. Geol. Surv., 1929, pp. 221–222.

[460] Linck, G., Die Bildung der Oolithe und Rogensteine, Neues Jahr. f. Min., Beil. Bd. 16, 1903, pp. 495–513. Über die Bildung der Oolithe und Rogensteine, Jenaische Zeits. f. Wiss., vol. 45, pp. 267–278.

[461] The maximum solubility of calcium carbonate in sea water at 17° to 18°C. is about 0.0191 per cent.

[462] The experiments of Murray, J., and Irvine, R., in Proc. Roy. Soc. Edinburgh, vol. 17, 1890, pp. 79–109, show that at a temperature of 34°F., calcium carbonate is precipitated as calcite, at 47°F. as a mixture of calcite and aragonite, and at 80°F. and above as aragonite.

[463] Vaughan, T. Wayland, Papers from the Tortugas Laboratory, Carnegie Inst. of Washington, vol. 5, 1914, pp. 49–54.

ranged in diameter from 0.004 to 0.006 mm. and did not have concentric structure. As the shapes of the cores of some of the oolites forming in the same waters are similar to the aggregates in the muds, he considered that it may yet be shown that the formation of the latter is initial to that of the former.[464]

Wieland[465] has suggested that siliceous oolites may have developed originally in the same manner as calcareous oolites. He states that many siliceous oolites have the silica arranged radially, with the particles projecting inward from an outer rind of concentric layers, suggesting a tiny geode and possible development from a bubble coated with silica. He further suggested that lime and silica may be deposited alternately on a single nucleus by chemical reactions reversible for these two substances, or silica and hematite, as is suggested by the observations of Smyth on the oolites of the Clinton hematites where siliceous shells are left after the hematite is dissolved.[466]

An interesting contribution to the oolite problem is that of Schade.[467] This arose from experimental work relating to gallstones, the experiments demonstrating that when a substance passes from the state of an emulsion colloid to solid form the resulting particles have radiate crystalline arrangement if the substance is pure, but if other substances are present, the particles have concentric structure. Bucher[468] has examined oolites from the point of view of the occurrences of the constituents in the colloidal state, and he comes to the conclusion that the assumption is justified:

> that most if not all, oolitic and spherulitic grains were formed by at least one constituent substance changing from the emulsoid state to that of a solid; that the spherical shape of the grains is due to the tendency of the droplets formed during this process of separation to coalesce; and that the difference between radial and concentric structure depends on the amount of other substance thrown out simultaneously with, and mechanically enmeshed in the growing structure.

Oolites in the Green River formation[469] do not have radial structure. The concentric laminæ are conspicuous and the oolites have a darker color

[464] Vaughan, T. W., Oceanography and its relations to other earth sciences, Jour. Washington Acad. Sci., vol. 14, 1924, p. 327.

[465] Wieland, G. R., Further notes on Ozarkian seaweeds and oölites, Bull. Am. Mus. Nat. Hist., vol. 33, 1914, pp. 248–255.

[466] Smyth, C. H., On the Clinton iron ore, Am. Jour. Sci., vol. 43, 1892, pp. 487–496.

[467] Schade, Heinrich, Zur Entstehung der Harnsteine und ähnlicher konzentrisch geschichteter Steine organischen und anorganischen Ursprungs: Zeits. f. Chemie u. Industrie der Kolloide, vol. 4, 1909, pp. 175–180, Über Konkrementbildungen beim Vorgang der tropfigen Entmischung von Emulsionskolloiden, Kolloidchemische Beihefte, vol. 1, 1910, pp. 375–390.

[468] Bucher, W. H., On oolites and spherulites, Jour. Geol., vol. 26, 1918, pp. 593, 609.

[469] Bradley, W. H., Algæ reefs and oolites of the Green River formation, Prof. Paper, 154–G, U. S. Geol. Surv., 1929, pp. 221–222.

than their matrix, the coloring being due to iron which is concentrated in them with respect to the matrix. It is postulated that the oolites in a dense matrix formed in an ooze or gel consisting of "colloidal ferric hydroxide with a large admixture of extremely finely divided calcium carbonate," and "it is possible that the calcium carbonate may also have been in a colloidal state." Bradley suggests that the absence of radial structure to the calcite may have been due to the

> protective action of the colloidal ferric hydroxide. . . . The ferric hydroxide must have been coagulated by negative ions as carbonate or chloride in the solution, and then because the minute coagulated particles are unstable in the presence of larger ones, and apparently also in the presence of any larger foreign particle such as a quartz or feldspar grain, they coalesced into spheres, mechanically enmeshing a considerable quantity of the suspended calcium carbonate. By that process the oolite grains grew. Apparently their growth was limited by the supply of ferric hydroxide, as they seem to have extracted the greater part of it from the matrix.

Bradley further suggests that the oolites not in a dense matrix may have been formed in the same way, but that the matrix was later washed away; also, that an ooze or a gel may not have been essential and that the oolites may have developed in fluids no more viscous than natural waters, these waters containing colloidal components as ferric hydroxide, silica, algal gelatin, or some other colloid. It is further suggested that the simultaneous precipitation of the colloid and calcium carbonate, the latter through action of plants or other agent, might lead to the formation of oolites in waters over almost any bottom and that the particles might grow while lying on the bottom.

The writer is of the opinion that many oolites have formed without suspension in an ooze or gel. The specimens derived from the hot-water coil and from pools on the floor of Carlsbad Cavern were certainly not in an ooze, and it does not seem that a colloid need be assumed for their formation any more than for the formation of the scale lining the wall of the same coil. The polyhedral pisolites described by Shrock do not seem to have formed in an ooze or gel unless the matrix was entirely utilized to form the pisolites. Oolites forming in an ooze or gel should appear as if floating in the matrix and more or less separated from each other.

The latest explanation of the origin of oolites is that of Mathews.[470] According to him, the Great Salt Lake oolites originate at the water's edge whence they are washed upon the mud flats and grow as driven inland by the wind. The laminæ correspond to seasons and result from the direct precipitation of amorphous aragonite from evaporation of capillary water.

[470] Mathews, A. A. L., Origin and growth of the Salt Lake oolites, Jour. Geol., vol. 38, 1930, pp. 633–642.

Growth takes place during early summer months when the rise of temperature is greatest. Little if any growth occurs in the water. The oolites on the bottom of the lake are small, with only one or two laminæ. The accumulation of soot on the exteriors of the crystalline laminæ of the oolites is considered proof that formation took place on land and that each band of soot was collected after the rainy season. Most oolites formed around some solid nucleus, and of 574 examined only 4 were found that might have formed around a gas bubble or an alga.

The depths at which oolites form have not been determined. Neither has it been shown what are the limits wherein oolites may be deposited. The preceding paragraphs show there is great difference of opinion relating to the environment of formation. At the present time oolites are being transported in sand dunes about the shores of some lakes and over sea bottoms wherever currents exist that can obtain them and are competent to transport them. If oolites are formed in the manner suggested by the observations of Vaughan, Linck, or Rothpletz, there do not appear to be any reasons precluding their occurrence to great depths unless pressure and light are factors in their formation. Perhaps high temperature is a factor. If so, they should at the present time develop in greatest abundance in the upper waters which are warm in contrast to the deeper waters which are cold, and in tropical waters rather than those of high latitudes. Modern oolites are most abundant in the warmer latitudes, but they also occur in temperate. Some hot weather seems to be a favoring factor. The writer does not consider that the facts warrant the sweeping assumption that oolite and pisolite formation require materials to be in the form of a colloid before they can participate in such formation. It seems probable that all of the material can be in true solution. The "shot" in laterites and pisolites in bauxite shows that a water cover is not required. The writer considers it reasonable to assume that no generalization relating to oolite and pisolite formation has universal application.

Colors of Sediments[471]

Colors of sediments may be either primary (original) or secondary, the latter a consequence of weathering and important in various residual ma-

[471] The manuscript for the topic on the colors of sediments given in the first edition of the Treatise on Sedimentation was prepared by Doctor Eliot Blackwelder and it was planned that such should be true of the manuscript for the second edition. The state of Doctor Blackwelder's health has precluded his assisting in the preparation. He has, however, read the manuscript and made suggestions for its improvement. Gratitude is due Doctor Blackwelder for this assistance. The material of the first edition has been freely used in preparing the manuscript of the second.

terials such as laterite and bauxite. The distinction between primary and secondary is more or less arbitrary, and in many cases there may be considerable difference of opinion as to whether a given color was syngenetic with deposition or developed subsequently thereto. Generally speaking, a color may be considered primary if it existed in the sediment at the time the latter was buried, but it is extremely difficult to prove such was the case except in those cases where colors are due to the original colors of composing detrital minerals.

Many sediments would be white if it were not for the admixture of other materials. This is exemplified by such rocks as limestone, gypsum, anhydrite, rock salt, bauxite, kaolin, and most quartz sandstones. Others are black or dark for the same reason, as coal and some graywacke and volcanic ash. The most common condition is for sediments to be composed of several ingredients, with corresponding variations in color. Color in some cases arises from the colors of the detrital minerals, but in many and probably most cases the colors result from organic matter or iron, the abundance or concentration of the former giving gray, blue, or black, and the degree of oxidation and combinations of the latter yielding yellows, browns, pinks, reds, blacks, and greens. Low states of oxidation give colors ranging from gray to blue, and higher from yellow to red. Organic matter plays a double rôle in that it not only imparts color to the materials of which it is a part, but through its reducing properties it may and is likely to take color from these associated materials.

The significance of the colors of sedimentary materials is an important but tantalizing problem. There is first the wide range of colors and the matter of referring them to some generally accepted color scale or chart. The generally used method of referring colors to one of the seven primary colors has little to recommend it and is extremely indefinite. The red of one geologist may be the brown of another. The color chart of Goldman and Merwin was designed to replace the inaccurate and generally meaningless methods of color designation in use prior to its preparation and still in use by many geologists.[472] Another problem connected with color is that of the condition of the rocks when observed. The colors of rocks are not the same when wet as when dry, and when in bright sunlight as when in shadow. Thus, many shales are blue when wet and gray when dry. Still another important problem connected with color is the latter's significance in terms of the environment of formation. This is a field wherein there has been

[472] National Research Council, 1928. Until something better is devised this chart should be used by every sedimentationist. It has been suggested that a photometer be used in determining colors of powders. Grawe, O. R., Quantitative determination of rock color, Science, vol. 66, 1927, pp. 61–62.

much speculation, as witness the oft repeated statement that red is indicative of aridity.

The various colors of sediments are divided into four groups: white to light gray, dark gray to black, green, and yellow to red. It is not to be understood, however, that there are sharp divisions among these groups, as such is by no means the case. Black, gray, yellow, brown, and red colors are common. Green is a not uncommon color, and blue is common in wet sediments, but less so in dry. However, many shales and some limestones and sandstones are blue.

WHITE TO LIGHT GRAY

The light colors indicate that the materials of the sediments are either finely divided or pure. Many limestones are white to light gray because composed of pure or nearly pure calcite or dolomite. The same is true for most gypsum and rock salt. Many clays are white, and such is the case for much bauxite. Most quartz sands are white to gray, and the resulting rocks may have the same color. Many feldspars are light colored; sands derived from these are white to gray, and they may yield rocks similarly colored. The presence of muscovite gives a more or less silvery white color.

DARK GRAY TO BLACK

Colors ranging from dark gray through blue to black are due in most cases to one or more of four varieties of constituents. These are: matter of organic origin, minerals intrinsically dark, certain sulphur compounds, and the black oxides of manganese. The most important of these four coloring agents is probably that of organic origin.

Organic matter is divisible into the carbonaceous and hydro-carbonaceous, the former including graphite and carbonized organic matter of all kinds, the latter asphalt, tar, and any of the dark colored hydrocarbon compounds. Carbonaceous materials may be sufficiently concentrated to give the black of coals and thence by gradual decrease to yield the less dark colors and the grays of many shales, sandstones, and limestones. The hydrocarbons have somewhat similar degrees of concentration and give different degrees of darkness to shale, limestone, flint, and sandstone.

Dark-colored minerals and rock fragments are probably second in importance in imparting dark colors to sediments. The minerals are chiefly the unaltered silicates of igneous and anamorphic rocks, among which are hornblende, biotite, augite, magnetite, and ilmenite. Dark rock fragments are derived from black slates, black flints, basalt, diabase, scoria, and obsidian, and these fragments in places are so abundant as to give dark colors to the clastic sediments derived from them. Conditions favoring accumu-

lation of such clastics are those of rapid rock breaking with limited decomposition, and thus they are most common in the conglomerates, graywackes, and tills of the colder climates. Pyroclastics very commonly have dark colors. Sediments which are dark colored because of the presence of dark minerals seem to be most common on beaches whereon magnetite, ilmenite, and other minerals produce dark-colored to black sands. Beach sands of such color are by no means rare and have been worked for gold and platinum on the coast of Oregon and for iron on the coast of Quebec and elsewhere. A black sand from Idaho contained ilmenite, garnet, magnetite, zircon, monazite, samarskite, titanite, columbite, polycrase, small percentages of thirteen other minerals, and also some obsidian.[473]

Some of the oceanic muds and certain other sediments deposited under water in the presence of a limited quantity of oxygen range in color from blue or gray to black, the blue seemingly largely due to the presence of water, as many blue shales become gray on drying. The colors of these sediments are largely or partly due to the presence of the black amorphous ferrous monosulphide, hydrotroilite, or the black ferrous disulphide, melnikovite. These same sediments also usually contain some organic matter to which they partly owe their color. As the two black sulphides are relatively unstable, they tend to crystallize on induration of the sediments into the more stable forms of marcasite and pyrite; this change takes darkness of color from the sediments, but the products rarely give color to the rock because the pyrite and marcasite usually are not present in sufficient quantity, particularly as they are associated with sediments which are already dark because of their content of organic matter. If the sulphides develop in sediments relatively free from organic matter, colors become light as the former change to marcasite and pyrite, and after exposure to the atmosphere a buff or tan color develops in consequence of oxidation of the sulphides, exposed surfaces having such colors, whereas fresh fractures may be blue, gray, or white. Thus, the white or gray Salem limestones of Indiana become buff after exposure to the agents of the atmosphere.

The black oxides of manganese form nodules and black coatings on rock fragments and detritals over many parts of the sea bottom, and color the fine sediments of some bottoms. Similar coatings are made over rocks in fresh waters. Black coatings also are made over rock fragments and rock outcrops in both dry and wet regions on land. Manganese oxides also impart dark colors to the deposits of some swamps and the residual soils of warmer latitudes. In comparison with the other materials imparting dark colors, manganese oxides are relatively unimportant.

[473] Shannon, E. V., Mineralogy of some black sands from Idaho with a description of the methods used for their study, Proc. U. S. Nat. Mus., vol. 60, 1921, pp. 1–33.

Black sediments are common in the geologic column and are known to be forming over many parts of the world. Among the black sediments are the peats, coals, black shales, the black muds of the limans of the Baltic and elsewhere, the black muds of fresh-water lakes, the black muds of the Black Sea (the Black Sea muds become lighter colored when dry), etc. Sediments within the range dark gray to blue and black are still more common. Blues are common in wet sediments, but some shales, sandstones, and limestones remain blue after drying. MacCarthy[474] ascribed this color to the presence of hydrated ferrous-ferric iron, but it seems likely that in some cases it is due to carbonaceous matter or mineral structure.

GREEN

The green colors of sediments are due to a considerable variety of minerals, but of these only two groups have more than local significance. They are such hydrous silicates as the serpentines, chlorites, and epidote; and glauconite. Green is not an uncommon color, being found in muds, shales, sands, sandstones, and some limestones. In many cases the coloring materials are iron-bearing, but such is not always the case. In the hydrous silicate coloring materials it seems that the iron is generally in the ferrous-ferric condition.[475] To the layman in geology the presence of green colors in rocks connotes the presence of copper, and in rare instances such is the case.

The hydrous silicates are common coloring minerals in shales, tuffs, and agglomerates. Many muds and shales are decidedly green, but not enough work has been done to be certain that a hydrous silicate is responsible, though chemical analyses showing a preponderance of ferrous iron would exclude glauconite as the coloring material.

In marine sediments, modern and ancient, a mineral frequently responsible for the green color is the hydrous potassium iron silicate, glauconite, in which ferric iron dominates over ferrous. Glauconite gives color to green sands and green muds which are peculiar to slightly reducing areas of slow deposition on the continental shelves and slopes. As previously noted, its distribution ranges from very shallow to very deep bottoms, and as a coloring material it is a constituent of many ancient sands. Whether many of the green shales of the geologic column owe their color to glauconite cannot be stated positively, but it has been more or less generally assumed that such is the case and that the glauconite is in a fine state of division. A somewhat similar mineral, greenalite, gives color to some of the Pre-Cambrian forma-

[474] MacCarthy, G. R., Colors produced by iron in minerals and the sediments, Am. Jour. Sci., vol. 12, 1926, pp. 17–36.

[475] Hager, D. S., Factors affecting the color of green sedimentary rocks, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 911–913.

tions of the Lake Superior region. This mineral contains no potash and has not been discovered in modern sediments, or sediments subsequent to the Proterozoic.

A greenish color in some cases is due to original colors of detrital minerals, as green hornblende, actinolite, uralite, bastite, and olivine. Such rocks are not of common occurrence, but in rare instances there is a local abundance. Thus, along some beaches of the Hawaiian Islands the beach sands are olive green because olivine particles are the most abundant constituent.[476]

In rare and local instances the green copper carbonate, malachite, serves as a color for shales and sandstones, but as a coloring material this mineral has little quantitative significance.

YELLOW TO RED

The colors ranging from yellow to red through buff, purple, brown, etc., are among the most common in sediments, particularly after the latter have become indurated and exposed to atmospheric action. Most residual materials of temperate and tropical regions have a color within this range. In most cases this color is lost in transportation, so that the color on deposition falls within the range of gray to black, this being due to reduction of the ferric oxides, usually more or less hydrated, to which yellow, red, etc., colors are due. As shown by Rogers,[477] these hydrated ferric oxides are almost entirely amorphous. He groups them into two divisions, using the name "hematite" for those giving a red streak and "limonite" for those which give a yellow-brown streak. Most sediments with colors of the range yellow to red probably contain mixtures of these oxides. Hematite gives color to some of the Red Beds and red soils. Laterite is red for the same reason, but the magnetic properties of some of the particles show that some reduction has taken place and that a part of the iron is in the form of magnetite. Hematite also colors limestones, cherts, and other rocks in varying degrees of intensity, and red limestones are not particularly rare. Yellow, buff, and brown soils and sediments probably have the iron in the form of limonite. This color is common in mid-temperate latitudes in subsoils under conditions of good drainage.

Some beach sands have various degrees of red due to the abundance of garnet particles. Such are not particularly common, but they may be seen on shores where igneous and anamorphic rocks are undergoing erosion, as along the shores of Lake Champlain, the east coast of Quebec, the Labrador

[476] Wentworth, C. K., and Ladd, H. S., Pacific Island sediments, Univ. Iowa Studies, vol. 13, 1931, p. 30.

[477] Rogers, A. F., A review of the amorphous minerals, Jour. Geol., vol. 25, 1917, pp. 515–541.

coast, and elsewhere. Many sands are colored pink to red because of the presence of pink to red feldspars. The Newark series of the eastern part of North America owes the red colors of some of its sandstones partly to the abundant presence of feldspar.

Detritals of red rocks in places compose the major parts of beach and other sands and gravels and are responsible for the color of the aggregate. The Keweenawan conglomerates near Calumet, Michigan, locally are made up in large part of detritals of jasper, red quartzite, red slate, and red felsitic lavas and are red as a consequence.

ENVIRONMENTAL SIGNIFICANCE OF COLOR

The environmental conditions determining the colors of sediments are not fully understood, but are of great importance. These conditions need to be appreciated and studied if past environments are to be visualized in any degree of accuracy. The environmental problems of color are clouded with traditional ideas and obscured by assumptions with little or no factual basis, as for instance the oft-repeated and erroneous statement that redness of sediments denotes aridity. The problems are here considered from the point of view of continental and marine sediment.

Continental Conditions Controlling Color

The most influential land factors influencing colors are: (a) the nature of the parent rocks, (b) the conditions under which they disintegrate or decompose, (c) the conditions at the place and time of deposition, and (d) diagenesis subsequent to deposition. The conditions under which transportation takes place are also important. The colors of the sediments deposited on land are resultants of the various factors, the particular color being determined by which factor or factors dominated.

In hot, rigorously arid regions the original colors of the country rocks largely govern the colors of the resulting sediments, and as rock powders and fine detritals tend to be lighter colored than their source rocks, the result is that desert sediments tend to be light. Acidic igneous and anamorphic rocks, themselves usually gray to pink in color, generally give rise to pale gray to flesh-colored products of weathering; the derivatives of basic igneous rocks are gray to dull brown, and red rocks yield red sediments. Pure quartz sandstones break down into white quartz sands, and limestones and gypsum produce white sands of these materials. If decomposition is small and subordinate to disintegration, the particles released for transportation may contain little thoroughly decomposed matter, and as decomposition likewise has little affected the particles resulting from disintegration, the original colors of the rock particles may be little changed. The rock particles

tend to be moved largely by wind and to be heaped into dunes of light-colored sands. The deposits of the playas and ephemeral streams are light- to buff-colored silts and salts of various composition. Prevailing colors of desert sediments produced within a desert are therefore light rather than dark, and white, buff, pale gray, lavender, and pink are characteristic, buff probably being commonest. However, it may be that sediments are produced outside of, but carried into a desert. Under these conditions the colors of the region of derivation are likely to be retained. There is a prevailing view that sediments of deserts are red; this is a tradition that is not supported by many examples.

The other extreme of temperature conditions gives such cold arctic and subarctic regions as Alaska, Labrador, etc., and the cold highland regions of the world. The sediments produced in these regions have undergone little decomposition and thus pattern their colors after those of the parent rock, with the difference that the low evaporation, high humidity, and generally higher precipitation favor the growth of vegetation, whose slow decay leaves a copious residue of black carbonaceous matter to be mingled with the region's sediments. This carbonaceous matter is generally present to some degree in all varieties of the sediments of such regions, even in sands and gravels, in the form of stems, bark, etc. Its immediate effect is to modify the colors of the original rock particles directly and primarily through its presence, and secondarily by reason of its reducing action upon any ferric compounds which the sediments may contain. The clays, silts, sands, arkoses, and gravels in which carbonaceous matter is present in not too great abundance are thus bleached to grays, and the color of the aggregate is prevailingly gray. As the organic matter increases, and such is likely to be the case over the lower areas, the colors become darker, and coal is at this extreme. The most common variety of sediments over the flood plains, deltas, and other lowland sites of deposition is blackish gray carbonaceous shale, and according to Blackwelder[478] such shales "are more abundant than all other subarctic deposits combined." The generalization is thus made that the sediments of the arctic and subarctic regions, where not modified by enclosed carbonaceous matter, have their colors, as in the deserts, largely determined by the colors of the parent rocks and minerals.

The tropical and warm temperate regions of plentiful rainfall have their rocks destroyed chiefly by decomposition. These regions have little or no frost action and have the surface permanently or perennially covered with vegetation, and nearly all rocks tend to decompose and have their soluble constitu-

[478] Blackwelder, E., Treatise on Sedimentation, 1st ed., 1925, p. 546; The climatic history of Alaska from a new viewpoint, Trans. Illinois Acad. Sci., vol. 10, 1917, pp. 275–281.

ents removed, leaving a residue largely composed of aluminum hydroxide, hydrous aluminous silicates, hydrous iron oxides, quartz, and a few other rather insoluble materials. Colors tend to be brown to red, but they may be gray if the vegetable matter is adequate to reduce the ferric oxides. These residual materials are quite certain to be transported and deposited in association with organic matter, and this association and the conditions at the times and places of deposition will largely determine colors. If a region is continuously moist and the places of deposition are subaqueous or on damp, poorly drained, flat surfaces, the ferric oxides are quite certain to be reduced to the ferrous form and appear as colorless carbonate or sulphate, either possible of removal, or of precipitation as carbonate or as black iron sulphides. Under such conditions much of the organic matter may not completely decay and may remain as blackish coloring matter in quantity sufficient to color the associated inorganic materials gray to black.

In most tropical and warmer temperate regions with sufficient relief to produce effective downward drainage through the surface and subsurface materials, oxidation of all iron compounds is probable, and the colors of the residual materials become brown to red. In tropical regions there is also likelihood of considerable removal of the silica and decomposition of the clay to produce aluminum hydroxide and silica, the latter probably in turn removed, leaving the regolith composed of aluminum hydroxide and hydrous iron oxides. The transportation of these sediments to and on lower and poorly drained levels is likely to incorporate considerable organic matter, with reduction of the iron and loss of the brown to red colors as sequels. The general results are that red sediments are not to be expected in the steadily moist and warm tropical and warm temperate regions and gray colors tend to prevail.

However, in tropical and warm temperate regions with a wet season alternating each year with one that is hot and dry, similar conditions of decomposition may prevail, and residual soils with the same colors of red to brown are produced; but the vegetation is eliminated or greatly reduced during the hot dry season, so that the quantity available for deposition with the sediments is small, and the latter retain their vivid colors after deposition. The same results are obtained if the red sediments are carried from a moist and warm region into a bordering one. Again, the red residual material may be produced in a region during a moist epoch and deposited during a succeeding dryer epoch. Good illustrations of these principles may be found in the Hawaiian Islands. The windward sides of the islands where they are exposed to the trade winds are continuously wet, and the hillside soils are brown to purplish red. After deposition on the river flood plains these soils, now sediments, become gray to black. On the leeward

side of the islands, where there is a short wet and a long dry season, the soils are brick-red and the sediments deposited on the river flood plains have the same color.

It is inferred that most of the red sandstones and shales of the geologic column were formed as thus outlined, that is, in a warm region with good underground water circulation and with seasons of warmth and dryness alternating with those of great rainfall and floods, and that deposition took place in a region of the same climatic character or in a semi-arid to arid marginal region or in a succeeding epoch of dryness. To these conditions are referred the Red Beds of the Rocky Mountain region and similar sediments elsewhere. These are not necessarily the deposits of deserts.[479] They may have been deposited under desert conditions, but they could not have originated there.

Marine Conditions Controlling Color

In the ocean and other large bodies of water not so salty as to prohibit the growth of many organisms, the prime factors responsible for color seem not to be climatic, but rather the sufficiency or insufficiency of oxygen in the bottom waters and especially in the interstices of the accumulating sediments, and the greater or less abundance of aquatic life.

Under aërobic or oxygenated conditions and slow accumulation of sediments all organic matter is apparently devoured by the many scavenger animals of the sea bottom or destroyed through bacterial decomposition, and none is left to accumulate with the sediments. Under some conditions glauconite forms and introduces a green component. Prevailing colors are therefore gray, cream color, or pale green, appropriate to the colors of the calcareous or siliceous shells, plant material, or associated muds. In deeper waters below the densely populated neritic bottoms the quantity of oxygen probably is smaller than in neritic waters, but so also is the organic matter, the result being that colors are not unlike those over the neritic bottoms with apparently a tendency toward darker hues, which arises from organic matter escaping oxidation or from the development of the black mono- and disulphides of iron. Glauconite may also form under these conditions. Accumulations of globigerina and other calcareous oozes have gray to cream colors consistent with the colors of the composing calcareous shells. In the deep abysses, lime carbonate passes into solution before reaching bottom, and the deposits are either composed of siliceous shells and insoluble residues, or of the latter alone. The former constitutes the diatom and radiolarian

[479] Barrell, Joseph, Dominantly fluviatile origin under seasonal rainfall of the Old Red Sandstone, Bull. Geol. Soc. Am., vol. 27, 1916, pp. 345–386; Relations between climate and terrestrial deposits, Jour. Geol. vol. 16, 1908, pp. 285–294.

oozes with gray, cream, and other colors, and the latter, because of the insoluble ferric oxides, is red, constituting the red clay. This red has been produced because of the sediments sinking through the thousands of feet of water and becoming oxidized while so doing, and it persists because of the rarity of organic matter on the very deep ocean bottom.

Under anaërobic conditions the action of scavengers and the oxidation of materials are largely decreased or even prevented. Organic matter is not completely destroyed, and the undestroyed portion becomes incorporated in the sediments, where it exercises a reducing action and takes ferric iron colors from the sediments and darkens them by its presence. These anaërobic reducing areas also become populated with sulphur bacteria forming the black mono- and disulphides of iron, which likewise give blackness to the sediments. Under slightly reducing conditions glauconite forms to impart a green component. The results are that the sediments have colors ranging from gray to green and black, and these are characteristic colors of the deep holes and places of poor circulation over the ocean bottom, as the deep fjords of the Norway coast, the deep Bay of Kiel, the holes in Chesapeake Bay, the deeper waters of the Black Sea, Lake Baikal, and many if not most deep fresh-water lakes. Here are formed the gray (often called "blue") muds of the continental slopes and the black oily shales of cul-de-sacs. However, all reducing areas are not in deep water. Marginal parts of a sea may be so shallow for some distance from the shore that there is no wave activity reaching the shore or seriously affecting the waters for some distance therefrom. This condition is favored by weak tides and is found in such existing seas as the Baltic and probably obtained in many epicontinental seas of past geologic periods. Under these conditions of poor circulation the fresh waters of the land mingle indifferently and slowly with those of the sea, and at a given place one frequently replaces the other. Plant life thrives more or less indifferently; scavengers have difficulty in existing; and the deposits are black like those in the limans on the east Baltic coast, the coast of the Black Sea, and a few places elsewhere. It is the writer's opinion that many black shales, as those of the New Albany, Chattanooga, etc., formed in shallow waters as outlined, thus representing the deposits made by a retiring sea or the initial deposits made by a sea advancing over a plain rising gently from sea level so that slight rises flooded great areas.

Some tropical rivers, as the Amazon and Orinoco, more or less continuously deposit red muds about their mouths. Varying amounts of organic matter become incorporated with these muds so that beneath the surface the ferric oxides responsible for the redness may become reduced and be converted into sulphides and carbonates, with loss of redness in the parts so affected and change of color to gray or black. How extensive such changes

are in these tropical muds cannot be stated, but it is considered unlikely that the redness persists far beneath the surface.

The red marine limestones not uncommon in the geologic column are usually inferred to have had that color from the beginning, and such may have been the case in some instances. Examples are the Devonian limestone of Percé Rock of Gaspé, part of the Hoburgen limestones of Gotland, and the Cambrian Smith Point limestones of Newfoundland. According to Galloway,[480] red calcareous deposits are not known to be forming today under marine conditions, and it is his conclusion that all red limestones are due to atmospheric weathering, a view in which White and others concur. The generalization seems to be too sweeping, however, and it may be that red calcareous sediments are deposited under certain marine conditions.[481]

The shore deposits of seas and lakes are affected by local influences, and particularly by the nature of the country rock, much more than are the off-shore deposits. Thus, along certain parts of the Alaska coast the sands and gravels are dark gray owing chiefly to the copious admixture of particles of black flint and black slate worn from the adjacent cliffs. Likewise, on some of the shores of the Hawaiian Islands the sands are brownish green, or even black, because of the comminuted basalt rich in olivine. Some of the sands of the Quebec coast are red, pink, or black due to garnet, feldspar, or magnetite. Examples of this character are numerous and in all cases are due solely to the comminution of unaltered rocks.

SUMMARY

1. Sediments whose colors are due to the composing detritals indicate one of several origins. They may have been formed under conditions of rigorous aridity, rigorously cold climates adjacent to steep slopes, or upon the beaches of lakes and seas. On land these colors denote either topography of considerable relief, or a climate either too dry or too cold to permit rapid decay of minerals. Colors of this origin in marine deposits have little or no climatic significance; they are due to a coastal terrane breaking down through wave attack, but frost action favors wave erosion.

2. Black is due largely to incomplete decay of organic matter under more or less anaërobic conditions in marshes, wet (and cold) plains, lakes, particularly those with no annual overturn, very shallow waters of tideless or almost tideless seas, and in deep holes of the seas and the ocean.

3. Grays, if dark, have something of the significance of black, but the

[480] Galloway, J. J., Red limestones and their geologic significance, Abstract, Bull. Geol. Soc. Am., vol. 33, 1922, pp. 105–106; White, D., etc. Discussion, pp. 106–107.

[481] Clarke, J. M., 60th Ann. Rept. New York State Museum, 1908, pp. 63–64. Clarke cites other authorities on the significance of red limestones.

lighter shades have a much wider range of origin. If the deposits are continental, several environmental conditions are possible. If the gray sediments contain evaporites, a desert playa or lake may be postulated. Similar grays without evaporites may develop in the flood-plain deposits of a river of a region with not too permanently wet climate. The gray sediments may be those of a delta, of parts of the neritic bottom or of the continental slopes, or they may have been deposited in very deep water.

4. Variegated colors, that is, those altering from one bedding unit to another, are considered characteristic[482] of continental deposits—river flood plains, alluvial fans, deltas, etc.—but it is known that such combinations also are found in the deposits of the neritic environment. The non-marine Morrison shales of Montana and Wyoming show this variation in decided development.

5. Green, when not due to green detritals, indicates chiefly the more or less altered pyroclastics or the glauconitic muds and sands of slightly reducing and slowly accumulating areas of the sea.

6. Red colors generally imply an origin of the composing materials under conditions of a water table sufficiently low to give good underground drainage, plenty of rainfall to support a good but not abundant growth of vegetation, and a warm climate comparable to that of the tropics all over the globe, though hot and dry seasons may have alternated with moist, as is the case in southern Oklahoma at the present time. Deposition took place under climatic conditions of hot and dry seasons alternating with rainy seasons, or under conditions of general dryness, deposition in the latter case occurring in a region and climate marginal to the region of origin of the sediments or in the same region, but in a geologic epoch subsequent to that in which the materials became red. Deposition may take place on river flood plains, deltas, or in shallow seas or lakes, but if much organic matter is buried with the red sediments, the red colors disappear. It may happen that a red terrane, as the Red Beds, under extremely arid conditions may yield red sediments, and this must be kept in mind in interpreting the significance of red in continental deposits. Red sediments also characterize over 50,000,000 square miles of the abyssal parts of the ocean basin. Pinks, lavenders, yellows, and other pale shades may be due to several unlike environments.

There is danger that the reader of the preceding paragraphs may form too simple a concept of the significance of colors in the sedimentary formations. In actual practice the geologist will often be confronted with cases which have had complex histories. For example, the Nile River carries out the products of chemical decay from the tropical rain forest into the

[482] Barrell, J., op. cit., 1916, p. 376.

arid climate of northern Egypt for deposition. Again, the products of glacial wear and frost disintegration around alpine mountains may be carried down by streams and deposited under conditions favoring rapid chemical decay *in situ,* as in northeastern India and Burma. Surface-deposited beds of ash and cinders in the Eocene formations of the San Juan Mountains of Colorado have become highly colored by the action of the thermal waters after the deposits had been buried in the course of subsequent eruptions. Such action produces colors entirely foreign to the original deposit. Likewise, one must be on his guard against mistaking for true colors those which have been induced by weathering. Surface exposures of a gray limestone may appear red from the products of residual decay. A black shale containing abundant pyrite grains may appear yellowish or gray on account of limonite stains or the efflorescence of soluble sulphates.

"In short, the color of each sedimentary bed must be regarded as a problem in itself to which simple rules cannot be applied blindly without danger of serious error."[483]

[483] Blackwelder, E., Treatise on sedimentation, 1st ed., 1925, p. 550.

CHAPTER VII

ENVIRONMENTS OR REALMS OF SEDIMENTATION

General Considerations

It has been repeatedly emphasized in preceding chapters that sediments are adaptations to environments and that their various characteristics are resultants of the rocks of derivation, the environments in which detachment from parent rocks took place, the environments through which transportation was effected, and the environments of deposition. Much has been said relating to environments of deposition. These are many and they differ more or less greatly. Furthermore, each environment passes laterally into others, the change being gradual in some cases, as that between the waters of the deep and shallow sea, and abrupt in others, as between a lake and its bordering swamp deposits. Also, environments are sequential, and the sediments of one pass vertically into others, the change being of various degrees of abruptness.

It is known that some environments are identifiable by the sediments deposited therein, and it is thought that there is a sedimentary reaction to every environmental difference. Many of these reactions are known, and their identifications permit the environments of origin to be determined. Certain sediments are known to be extremely sensitive to environmental factors, and when all the facts are known it is thought that most if not all sediments will be found to have a high degree of environmental sensitivity. Too little attention has been paid to the influence of the environment from the points of view of both the sediments forming therein and the organisms living upon and in these sediments. It is a field inviting research.

Environments are possible of classification upon a variety of bases. That which seems best to the writer has the two major divisions of continental and marine. As these two environments have contact along the shoreline, the result is that an area adjacent to this shoreline partakes of the character of both, giving a third division of mixed continental and marine. The continental environments in turn are subdivided on the basis of whether the deposits are made by aqueous or non-aqueous agencies. The factor of depth of water is the basis for classification of the marine environments, and

the mixed continental and marine environments are subdivided very largely on a physiographic basis. The various environments are as follows:

- Continental environments
  - Terrestrial
    - Desert
    - Glacial
  - Fluvial
    - Piedmont
    - Valley-flat
  - Paludal (swamp)
  - Lacustrine
  - Cave (spelean)
- Mixed continental and marine environments
  - Littoral
  - Marginal lagoon
  - Estuarine
  - Delta
- Marine environments
  - Neritic or shallow water
  - Bathyal or intermediate depths
  - Abyssal or deep sea

It should be fully realized that these divisions and subdivisions are purely arbitrary and that by some variety of gradation each may pass into one or several others. Thus, the valley-flat environment of streams passes into that of the delta, and the latter into the shallow-water marine. The valley flat contains lakes, and the deposits of one may pass laterally and vertically into the deposits of the other. The sediments should, however, show the transitions.

Continental Environments

Continental environments may be divided into terrestrial, or those in which water plays a subordinate part in the deposition; fluvial, in which flowing water is the chief agent of deposition; paludal, in which the deposits accumulate in swamps through merely falling from the animals and plants which form them; lacustrine, in which the deposition is in lake waters; and caves. The terrestrial environments may be placed in the two groups of desert and glacial. In the desert environment the deposits are largely of wind and temporary water deposition; in the glacial environment ice and water derived from its melting are the chief depositing agents. The fluvial environment may be divided into that of the upper portions of streams, here designated the piedmont environment, and that of the other portions of streams exclusive of the deltas, designated the valley-flat environment.

TERRESTRIAL ENVIRONMENTS

The Desert Environment and Its Sediments[1]

It is estimated that one-fifth of the present earth's surface is without drainage to the oceans and that the approximate area of the arid regions of the earth is 11,500,000 square miles.[2] Thus, regions of existing desert environment are of great extent, and such must have been the case to some extent during every period of geologic time. However, only small parts of a desert are places of deposition. The Sahara contains 3,500,000 square miles; 700,000 square miles are dune- or sand-covered; the remainder has a rock floor.[3] In other words, four-fifths of the desert is being eroded, and it is thought that this figure is below the average. Contrary to popular conception, only small parts of deserts are covered with drifting sands.

The sediments of deserts accumulate by wash from upland slopes, by streams whose channels at times are filled with torrents of muddy water and at other times are dry coulees, by deposition from waters of ephemeral and salt lakes, and by deposition from the atmosphere.

The essential condition necessary for a desert environment is that vegetation does not grow or grows with difficulty. This may be due to lack of rainfall, low temperature, infertility of soil, and continued covering of a surface by sediments. The desert environment due to lack of sufficient rainfall is the most important at the present time, but before the advent of land-plant life large areas of low rainfall must have received many sediments having the characteristics developed in the desert environment. It is not certain that these have ever been identified. The existing large deserts are on the leeward sides of mountains, in the trade-wind belts, and on warm lands leeward to cold waters. Low temperature at the present time is not an important factor in creating desert environment, but during the Pleistocene, regions marginal to the retreating ice sheet may have been of desert character, and they certainly received deposits which appear to be of wind deposition, the loess anterior to the front and perhaps dunes nearer the ice. Infertility of soil and repeated covering of a surface with sediments give rise to small desert areas in other environments. Cold climate and infertility of soil deserts are not considered in this connection.

A typical mountain desert basin—and most deserts to some degree will exhibit the same characteristics—has three distinct parts:[4] the rock moun-

[1] Walther, J., Das Gesetz der Wüstenbildung, 4th ed., 1924. This should be read by every one interested in desert geology.

[2] Murray, J., Origin and character of the Sahara, Science, Vol. 16, 1890, p. 106.

[3] Cana, F. B., The Sahara in 1915, Geog. Jour., vol. 46, 1915, pp. 333–357.

[4] Tolman, C. F., Erosion and deposition in the southern Arizona 'bolson' region, Jour. Geol., vol. 17, 1909, pp. 136–163.

tain slope on parts of which there may be considerable moisture and therefore vegetation, the graded piedmont slope and pediment[5] more or less covered with débris from higher lands, and the central lake, playa, or dry lake bed. The mountain slopes are covered with loose boulders ranging to 5 or 6 or more feet in diameter; on the pediment the range is to about 6 inches in diameter.[5] The mountain slopes are sites of active erosion. Such is also the case upon the mountainward portions of the pediments. The graded piedmont slopes and the central basin are sites of deposition, and the depositional area may be extended by filling of the basin and upward advance of the deposits upon the pediment, each advancing mountainward. However, the central basin may not entirely be given over to deposition, as deflation may be active and removal thus keep pace with, or even exceed, deposition. Such may also be the case on the higher areas of the desert where the only deposits may be in the temporary streams.

CHARACTERISTICS OF THE DESERT ENVIRONMENT. The most important characteristics of the desert environment are the scarcity of vegetation and special adaptations in the vegetation that is present, physiography, nature of the rainfall, salt and ephemeral lakes, occasional wholesale destruction of animals, methods of rock destruction, methods of transportation and deposition, and character and association of deposits.

Desert Vegetation. The vegetation of the desert is especially adapted to the conditions. Four types may be distinguished. One is perennial, with long tap roots, the length of the roots being altogether out of proportion to the heights of the plants above ground. Such flourish over those desert areas where ground water is not too far from the surface to be reached by roots. A second type has structures for storing the water which falls during rainy seasons, and these also have structures which minimize transpiration. The third type is found in semi-arid rather than arid regions, the plants being either annuals or biennials. The annuals spring up rapidly during the rainy season, develop quickly, seed, and die. The biennials start growth during the cool weather of autumn and seed during the moist weather of spring. The roots of this third group are characteristically close to the surface and wide spreading. The same type of root develops in swamps. A fourth type is adapted to a small use of water and has leaves minimizing transpiration. These plants are perennials and are represented by the sage, creosote bush (*Larrea mexicana*), grease wood (*Sarcobatus*, *Atriplex*, or *Grayia*), etc. A characteristic of most desert perennials is the possession of spines, and such are also borne by many annuals.

[5] Bryan, K., Erosion and sedimentation in the Papago country, Arizona, Bull. 730-B, U. S. Geol. Surv., 1922, pp. 52–66; McGee, W. J., Sheet-flood erosion, Bull. Geol. Soc. Am., vol. 8, 1897, pp. 92, 110; Lawson, A. C., The epigene profiles of the desert, Univ. California Publ., Geol. Bull., vol. 9, 1915, p. 34.

Desert Physiography. Desert physiography is somewhat different from that of more humid regions. It is due either to destruction or construction. In the region of destruction sand may be so abundantly carried by the shifting air currents as to seek out every weak spot in the exposed rocks. Hollows may be developed in loose or easily eroded materials. In the desert of Gobi these hollows "range from about 300 yards to 30 miles or more in length and from 50 to 400 feet in depth."[6] The depths are limited by ground-water level. Erosion cavities in rock walls range from shallow excavations to deep caves, and the wall rocks which bound the cavities are little decayed. As drifting sands stay close to the ground, much erosion may take place about the bases of cliffs, and these become very steep to overhanging. Rocking stones, mesas, buttes, mushroom rocks, caves, and etched surfaces are characteristic features of those portions of a desert where deflation dominates. The central region of construction may be a salt-encrusted mud flat or salt lake with marginal mud-flat and dune areas, or it may be entirely covered with dunes. The surfaces of the mud flats or playas are gently sloping toward the lowest parts; the dune areas have the irregular topography characteristic of such. The higher areas are mostly bare and etched rock surfaces covered with those rock particles not yet moved or too large to be moved by the existing agents of transportation. The final stage of the desert cycle is a flat plain covered to a greater or less extent by rock fragments resulting from wind blasting, insolation, and some chemical action.[7] The lowest areas may be salt or mud flats, and intermediate areas alone may correspond to popular conceptions of deserts.

Desert Rainfall. Although generally without rainfall, deserts occasionally have water falling in torrents and flowing to the low parts more or less in the form of sheets. McGee[8] states that within half an hour after a local rain in the Santa Rita Range of Arizona a sheet of water "thick with mud, slimy with foam loaded with twigs, dead leaflets, and other flotsam" appeared on the lowlands, "advancing at race-horse speed at first, but, slowing rapidly, died out in irregular lobes." The water "was nowhere more than 18 inches deep, and generally only 8 to 12 inches." In half an hour the water had almost disappeared, leaving over the surface a deposit of the débris it had carried. The débris of the higher lands is thus washed into the depressions where it is deposited with structures ranging from extreme

[6] Berkey, C. P., and Morris, F. K., Origin of desert depressions, Abstract, Bull. Geol. Soc. Am., vol. 36, 1925.

[7] Passarge, S., Über Rumpfflächen und Inselberge, Zeits. d. deut. geol. Gesell., vol. 16, Protokol, 1905, pp. 193–215; Davis, W. M., The geographical cycle in an arid climate, Jour. Geol, vol. 13, 1905, p. 393; Free, E. E., Bull. 68, Bur. Soils, U. S. Dept. Agric., 1911, p. 37.

[8] McGee, W. J., Sheet-flood erosion, Bull. Geol. Soc. Am., vol. 8, 1897, pp. 101–10.

irregularity to the finest of laminæ. Seasonal rains and glaciers of bordering highlands may bring some water into a desert. The volumes of water falling during some of the torrential rains may change the lower parts of a desert region into a vast shallow lake, Russell stating that the Black Rock Desert of northwestern Nevada has been changed in a few hours from dry burning sands to a lake with an area of 400 to 500 square miles which was not more than a few inches deep. This lake was impassable because of the softness of the mud of its bottom, but in a few weeks this became so dry that it was broken into polygons by mud cracks and so hard that a horse's hoof hardly made an impression.[9] Lake Goongarrie of western Australia presents a similar change of appearance. This lake is one of the so-called "dry lakes" and usually it is a "vast, smooth, bare surface, frequently white owing to a film of salt," but during times of moderate rainfall it becomes a wide sheet of water.[10]

Salt and Ephemeral Lakes of Deserts. The central depressions of deserts may be the sites of permanent salt lakes or playas, the latter covered only occasionally with water. In the salt lakes are deposited salts commensurate with those brought from the surrounding regions. The playas contain salty waters following rains, but during the intervals between rains they are either salt-encrusted or sand-, silt-, or clay-covered surfaces, the silt and clay (generally known as adobe in the southwest) containing crystalline particles of salts whose development crumbles and comminutes the silt and clay, thus rendering these easily susceptible to the attack of deflation. Mud cracking develops on an extensive scale, many cracks extending downward for several feet and being several inches wide at the top.

Destruction of Animals about Desert Lakes. Most desert regions are permanently inhabited by some animals, and others wander in during the seasonal development of vegetation. The indigenous animals are adapted to the dry condition and are little affected by the moisture conditions. With the decrease and final disappearance of the vegetation the migrant animals may not leave the region but may congregate about the water holes and ephemeral lakes, where they leave their tracks in the mud and ultimately die in large numbers. The flesh of herbivores is eaten and their bones gnawed by carnivores and carrion feeders, and many of the eaters ultimately add their bones to those already about the holes. These bones

[9] Russell, I. C., Present and extinct lakes of Nevada, Physiography of the United States, Mon. 4, 1895, pp. 105–110.

[10] Jutson, J. T., The sand ridges, rock floor and other associated features at Goongarrie in sub-arid western Australia, and their relation to the growth of Lake Goongarrie, a "dry lake" or playa, Proc. Roy. Soc. Victoria, vol. 31, n. ser., pt. i, 1918, pp. 113–128; The process of wind erosion in the Salt Lake District, Bull. 61, Geol. Surv. Western Australia, 1914, pp. 142–158.

lie on the surface until the next rain, when they may be buried, but in sediments whose porosity is high or whose mud cracking produces repeated exposure to the action of the atmosphere, there is little chance of permanent preservation. The great abundance of tracks in the Newark sandstone of the Connecticut Valley perhaps tells a sequence of this character—tracks are extremely abundant, but bones are exceedingly rare.

Methods of Rock Destruction. Bryan[11] states that mechanical methods of rock destruction consist of ruption and spalling, exfoliation, and granular disintegration, changes of temperature being held to be responsible. Mechanical methods of destruction are generally considered to dominate over the chemical, but Blackwelder[12] has emphasized the importance of chemical decay and minimized the effect of changes of temperature in desert regions, and Bryan states that "loose boulders are marked by concentric bands of color showing solution and deposition." The rather common presence of desert varnish shows some chemical activity on the surface materials, and it seems obvious that more exists beneath the surface. Blackwelder's[13] summary of the processes producing rock fragments in deserts states that insolation is not important, stream corrosion is minor, wind abrasion is rarely conspicuous, frost action is locally important, and chemical weathering and diastrophism are very important. The chemical processes are either neutral or oxidizing except in the desert lakes wherein reducing processes may exist.

Methods of Transportation and Deposition. It has been previously noted that transportation in arid regions is effected by sheet floods, ephemeral streams, and mud flows. After the materials become dry, all loose materials within the competency of the winds pay tribute to that form of transportation, the sands being swept into dunes and the fine materials lifted from the surface and carried from the desert. Blackwelder[14] has shown that deflation is of importance in thus removing dust, the Danby playa of southeastern California having thus been lowered 12 to 14 feet, remnants in the form of small mesas and buttes showing the former elevation. Walther, Richthofen, Udden, Keyes, and others have urged the importance of deflation in lowering the surface of desert regions.[15] Black-

[11] Bryan, K., op. cit., pp. 39–42.

[12] Blackwelder, E., Exfoliation as a phase of rock weathering, Jour. Geol., vol. 33, 1925, pp. 793–806; Barton; D. C., Notes on the disintegration of granite in Egypt, Ibid., vol. 24, 1916, pp. 382–393.

[13] Blackwelder, E., Desert weathering, Bull. Geol. Soc. Am., Abstract, vol. 38, 1927, pp. 127–128.

[14] Blackwelder, E., The lowering of playas by deflation, Am. Jour. Sci., vol. 21, 1931, pp. 140–144.

[15] For papers by Udden and Keyes see Geologic Literature of North America, Bulls. 740, 741, U. S. Geol. Surv., 1924.

welder's paper gives a factual quantitative basis to former opinions and permits the view that removal of materials may be quite rapid.

Characters and Associations of the Deposits of the Desert Environment. The deposits of the desert environment are more or less etched, varnished, and polished lag gravels over the pediments and other areas not sites of deposition of fine materials; quartz and other sands and pebbles and gravels in the dune areas around and within some of the depressions and in the stream channels crossing the pediments; clays, silts, and evaporation products within the depressions; and coarse piedmont deposits about highland areas within or marginal to the desert. Thus, there may be torrential stream, sheet-flood, and mud-flow deposits about the highland areas; eolian and fluvial deposits in an intermediate belt; and a depression deposit of more or less mud-cracked clays and silts or these with evaporation products. Sands of deserts, as elsewhere, should be mainly quartz, but some may be feldspar, calcite, dolomite, gypsum, etc. The sphericity may be high and many of the particles have mat surfaces. Minerals of low stability are likely to be present to some degree in most sands.[16] It seems likely that the minerals of the clays should be those of the early stages of decomposition and that much of the fine materials should be powdered rock and not composed of clay minerals.

Although much of a pediment may be bare rock surface veneered with lag gravels, the deposits upon it often attain great extent and not only mantle the feet of the highland areas, but extend up the valleys of streams into the highlands so that the mountains appear to rise out of the gravel accumulations. According to Blanford,[17] the gravel slopes in Persia range from 1° to 3°, and the accumulations attain their greatest dimensions over the drier areas. These deposits are fan-shaped, have their surfaces covered with gravel, cobbles, and boulders, and are evidently alluvial fans. The Shinarump conglomerate of the arid southwestern regions seems to be of desert piedmont origin. It "is everywhere lenticular; lenses of conglomerate overlap lenses of coarse and fine sand, and plasters of pebbles many feet in area or long, narrow cobble pavements appear and disappear within the formation in a capricious manner. Cross-bedding is characteristic; short laminae meet each other at large angles, and longer beds form smaller angles with the horizon."[18] The Overton fanglomerate[19] of Nevada is

[16] Reed, R. D., Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 1023–1024.

[17] Blanford, W. T., On the nature and probable origin of the superficial deposits in the valleys and deserts of central Persia, Quart. Jour. Geol. Soc., vol. 29, 1873, pp. 493–503.

[18] Gregory, H. E., Geology of the Navajo Country, Prof. Paper 93, U. S. Geol. Surv., 1917, p. 39; Longwell, C. R., Geology of the Muddy Mountains of Nevada, Bull. 798, U. S. Geol. Surv., 1928, pp. 52–54.

[19] Fanglomerate. A term proposed by Lawson, A. C., for the materials of alluvial fans. The petrographic designation of alluvial-fan formation, Univ. California Publ., Dept. Geol., vol. 7, 1913, pp. 325–334.

considered to be a deposit of an arid country of high relief and is stated to be like the alluvial fan formations now forming in the same region. The materials are unsorted,

the fragments in each thick layer or lens averaging coarser at the base than at the top, but in all beds pebbles and boulders of various sizes are jumbled together, their long axes trending in all directions. . . . In places many large boulders are banked together, with little finer material between them, but as a rule the matrix of pebbles, sand and cement envelops each boulder. Some boulders of the largest size occur isolated in a matrix of small pebbles and sand. In a large way the bedding planes are regular and parallel, but in detail irregularity is extreme, lenses everywhere interfingering. Thick narrow lenses of sand essentially free from pebbles occur, but they are exceptional in this phase of the formation.[20]

In the region about Goongarrie, western Australia, the sediments of the desert, here not extreme, are gully deposits of coarse detritus which are 2 to 6 feet thick and situated in longitudinal valleys of bordering highlands on the west; piedmont slope deposits lying upon gently sloping plains, composed of coarse detritus 6 to 8 feet thick, and formed by the coalescence of alluvial fans on the sides of the valleys; deposits on gentler slopes composed of a thin veneer over the underlying rock; samphire (salt-loving plants) flat deposits consisting of sands and clays in which locally there is considerable crystalline and powdery gypsum, sand ridges almost entirely restricted to the lake area and consisting of small, low, irregularly shaped ridges 3 to 8 feet high which eastward gradually pass into long, regularly shaped ridges 8 to 30 feet high, and westward into ridges smaller than those in the middle; and the deposits of the lake floor which consist of silt in which some fine sand is present. The silt usually has a dark red color and is commonly impregnated with sodium chloride and contains many crystals of gypsum. It has a determined thickness of 12 feet. The dunes are composed of small, rounded grains which are chiefly quartz and, subordinately, ironstone.[21]

Calcareous concretions may develop in the fine sediments containing considerable calcium carbonate. Not infrequently these are hollow and have cracked or bread-crust exteriors. The colors of the muds and silts range from gray through red and brown to black. The black is due either to carbonaceous matter or iron sulphide. On exposure the sediments with black colors due to iron sulphide become reddish. The silts and fine sands deposited in the lakes and playas may be beautifully ripple marked with symmetrical ripples; current ripples may also be present. These structures may be almost obliterated in the deposits of the playas, however, by reason of the action of salts in the clays and silts by which the mud on drying is

[20] Longwell, C. R., op. cit., 1928, pp. 68–74.
[21] Jutson, J. T., op. cit., 1918, pp. 113–128.

reduced to powder. Mud cracks are likely to be abundant in all sediments which permit their formation; the cracks may be deep and wide. There is likely to be much cross lamination of eolian origin in sand deposits. The central portions of the depressions may have evaporation deposits, and these may also have deposits of iron carbonate and silica. Some of the lakes may be margined by swamps, and small swamps may lie among the dunes. There is thus an intermingling or interlensing of deposits made by water, ranging from those of extremely torrential streams to those of small bodies with weak wave and current action, and those made by wind. The deposits made by water range from very fine to very coarse. Those made by wind are mostly sands. Marginal and leeward to the desert environment should be deposits of loess, and some dust may be deposited with coarse sediments to fill the interstices among them.

The sediments of the desert environment usually may be little oxidized. Some reduction may occur in the lakes and over the salt-encrusted flats. On the whole, neither oxidation nor reduction is particularly obvious. The colors of sediments under the conditions of a rigorous desert environment are light unless the country rock has other colors. Under less rigorous conditions oxidation may occur and the colors change to browns and reds. After deposition there may be introduction of iron, or oxidation of iron compounds, with consequent reddening of the sediments. Such seems to have occurred in the case of the sands of the Arabian desert described by Phillips.[22] This desert, known as the Nefud, has a width of 150 miles and an extreme length of 400 miles. It contains such ridges and depressions as characterize deserts, but the sands are not in motion, and except on the highest summits of the sand hills, the surface is thickly sprinkled with vegetation. The redness of the sands is due to a mere film over the rounded grains, the iron oxide being only 0.21 per cent of the weight. It seems obvious that the iron oxide could not have been present when the sands were in motion. Sands from the Sahara Desert, near the village of Aoulef Cheurfa, about a thousand miles south of the Mediterranean Coast, are a maroon red, but the iron oxide is only a small per cent of the whole. The time of formation of this color is not known.[23]

A summary of the characteristics of the deposits of desert environments is as follows: The stratification ranges from that of the laminated or bedded clays of the lakes and playas through the wedge-shaped cross-laminated units of the wind-deposited sands to the almost unstratified gravels of the

[22] Phillips, J. A., The red sands of the Arabian desert, Quart. Jour. Geol. Soc., vol. 38, 1882, pp. 110–113.

[23] These sands were obtained through the kindness of Mr. Alonzo Pond of the Logan Museum of Beloit College, Wisconsin.

piedmont slopes. The material is mostly light colored when deposited and, except for the evaporation and chemical deposits of the depressions, of mechanical deposition. The finer sediments may contain much calcareous matter and other products of evaporation. The fine sands and silts may be wave and water-current ripple marked, and the fine to coarse sands may have eolian ripple mark, the latter difficult of preservation. Tracks of organisms may occur locally in great abundance; skeletal matter is not common. The thickness of deposits which may accumulate in the desert environment has not been carefully investigated, but it would seem that 1000 feet would be a fair maximum, although conditions are conceivable which might make a greater thickness possible. There is a dovetailing of salt lake, playa, dune, and piedmont deposits and the occasional occurrence of black shales of lake and swamp origin. It needs to be emphasized that the entire set-up of the environment must be present in order to establish that a given sedimentary deposit was made in the desert environment. It seems probable that a deposit similar to any formed in the desert environment may form under other conditions. Thus, deposits of evaporites, wind-blown sands, or ventifacts do not prove a desert. The tendency to assume an ancient desert every time eolian cross-lamination, sand grains of high sphericity with frosted surfaces, ventifacts, or evaporites are found needs discouragement.

Deposits of Past Desert Environments. The oldest deposits which have been ascribed to deposition in desert environments are the Torridonian sandstones of Scotland and the Eophyton sandstones of Sweden. Ventifacts have been described from each. If these were deposited in desert environments, there are few reasons for believing that the conditions were arid, and the desert areas may have been due more to the absence of a land vegetation than to dryness. It would appear that deposits of the desert environment should be extremely abundant in the geologic column until the time of development of vegetable protection, and if general conceptions of the absence of a vegetable cover over the lands of Pre-Cambrian times approximate correctness, there should be extensive deposits with desert characteristics in the systems of those times.

Desert conditions possibly obtained in the deposition of parts of the Old Red Sandstone of Britain. Grabau and Sherzer have assigned the deposition of the Sylvania sandstone to a desert environment.[24] The particles of this sandstone are clean, well rounded, and well sorted grains of quartz of nearly uniform size. The rock is white and ordinarily very poorly cemented. The stratification and cross-lamination are said to have the characteristics

[24] Grabau, A. W, and Sherzer, W. H., The Sylvania sandstone; its distribution, nature and origin, Michigan Geol. and Biol. Surv., Publ. no. 2, 1909, pp. 61–86.

of those of eolian deposition. Grabau and Sherzer state that these sands are superior in sphericity and uniformity of dimension to the sands of most desert areas, or they "*out-Sahara* the Sahara sands" in rounding, purity, and assorting. If the Sylvania sandstone originated in a desert environment, and the evidence for this seems to be only the cross lamination of the sands and their shapes and surfaces, the conditions must have been extremely rigorous.[24]

The Triassic of England bears the features suggestive of desert origin in the cross-laminated sands of uniform grain, wedge-shaped units, dovetailing of stream-deposited gravels, piedmont deposits marginal to highland areas, thickening and thinning of the deposits, clay lenses of lake deposits with beds of salt and gypsum, etc.[25] The Triassic deposits of eastern United States have been inferred to have originated in the desert environment, but they are best interpreted as the deposits of an environment bordering on aridity. They will be further considered in connection with the piedmont phase of the fluvial environment.

Because of the occurrence of well worn quartz grains in the Chalk of both England and France it has been suggested that the lands surrounding the waters in which the Chalk was deposited were hot deserts of the Sahara type. Although the suggestion may approximate correctness, it is certain that the evidence on which it is founded is possible of other interpretation.[26]

The close of the Pennsylvanian saw the raising in Europe of the Hercynian mountains extending from southern Ireland to central Europe. Northern Europe was separated by these mountains from the seas of the time and became arid during the Permian and parts of the Mesozoic. During the early Permian the deposition of red beds appears to indicate oxidizing conditions at the sources of the sediments and dry conditions over the sites of deposition. During the deposition of the salt deposits rigorously arid conditions probably obtained. The Permian red beds of the western parts of the United States were probably deposited under semi-arid to arid conditions. The Lyons formation of the red beds of Colorado has been interpreted[27] as the deposit of the desert environment, but the films of ferric oxide which cover the quartz grains, if primary, preclude the possibility of rigorously arid conditions.

[25] Lomas, J., Desert conditions and the origin of the British Triassic, Proc. Liverpool Geol. Soc., vol. 10, pt. iii, 1907, pp. 172–197; Geol. Mag., vol. 44, 1907, pp. 511–514, 554–563. Beasley, H. C., Some difficulties with regard to the formation of the upper Keuper marls, Proc. Liverpool Geol. Soc., vol. 10, pt. ii, 1906, pp. 79–97.

[26] Bailey, E. B., The desert shores of the Chalk seas, Geol. Mag., vol. 61, 1924, pp. 102–116.

[27] Tieje, A. J., The Red Beds of the Front Range in Colorado, a study in sedimentation, Jour. Geol., vol. 31, 1923, pp. 198–202.

The deposition of the Jurassic sandstones (La Plata, Wingate, Todilto, Navajo) of southern Utah and parts of adjacent states seems to have taken place in the desert environment.[28] These sandstones range in thickness from 2000 feet in their southern distribution to 500 feet in southwestern Colorado, and the assumed desert over which the sandstones accumulated is estimated[29] to have had an area nearly equal to the sandy portion of the Libyan desert of northeast Africa. This desert is thought to have bordered the Jurassic sea on the south. The sandstones in the White Cliff formation are generally white; the grains are uniform in size, well rounded, have frosted surfaces, and are mostly of clean quartz. An iron oxide coating is generally wanting. Some bands of sandstones, 75 or more feet thick, show essentially no bedding.[30] Other beds are highly cross laminated with both eolian and aqueous types present, the latter indicating the existence of streams and other bodies of water, for whose presence additional evidence is given in the conglomerates and aqueous ripple marks. Some of the sandstones are red. Sandstones which may be of desert or semi-desert origin occur in the Comanchean of Kansas, and the white sandstones beneath the Magnesian limestone of England may have developed in an arid environment. Possibly parts of the St. Peter and Cambrian sandstones of the upper Mississippi Valley may be of eolian deposition, but neither can be held to have developed in typical desert environments. It is probable that deposits of the desert environment will ultimately be discovered in every geologic system.

The Glacial Environment and Its Sediments[31]

The glacial environment is characterized by low temperature, excess of snowfall over dissipation, abundance of water during the melting season, and erosion and deposition. At the present time this environment has great extent and its deposits great importance, but during those times of the geologic past when the environment possessed continental proportions its deposits covered areas as extensive as those of most other environments. At the present time there are over 60,000 square miles in Alaska which are receiving glacial or fluvio-glacial sediments.[32]

The conditions about the margin of a glacier have been so often described

[28] Longwell, op. cit., 1928, pp. 62–68; Gilluly, J., and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in Utah, Prof. Paper 150–D, U. S. Geol. Surv., 1928, pp. 70, 72; see also Gregory, H. E., Prof. Paper 93, 1917.

[29] Grabau, A. W., Comprehensive geology, pt. ii, 1921, p. 648.

[30] Cross, W., and Ransome, F. L., Rico Folio, no. 130, U. S. Geol. Surv., 1905, p. 5.

[31] Summaries of North American studies of glacial sediments have been prepared for a number of years by Doctor M. M. Leighton and published in the annual reports of the Committee on Sedimentation.

[32] Tarr, R. S., and Martin, L., Glacial deposits of the continental type in Alaska, Jour. Geol., vol. 21, 1913, pp. 289–300.

that only the barest outline is here given. At the immediate margin is a frontal moraine bordered on the stoss side by kame deposits and those made in small ponds. On the lee side of a moraine is outwash, beyond which are valley deposits of streams which form from the melt waters flowing over the outwash. As a glacier retreats, the successive moraines constitute dams between which lakes form, and in these are deposited lake or varve clays. Beneath a glacier is the ground moraine consisting of drumlins, eskers, and unorganized drift. As a glacier retreats, the ground moraine receives deposits of outwash and lake clays, the latter in many instances later becoming overlain by marl and peat. The evaporating ice and the outwash plains supply dust which is carried by wind to areas beyond the ice front and deposited as loess. These outwash plains may also be the sites of dunes.[33] Successive advances and retreats of an ice sheet may superimpose a succession of these deposits.

PROCESSES OF THE GLACIAL ENVIRONMENT. These have already been considered in detail. It may be repeated that chemical action is extremely limited in the glacial environment and in many instances deposits are made which are supported by ice either in the form of buried blocks or by a glacier itself and that the melting of this ice leads to slumping and contemporaneous deformation. Further, ice floating in the lakes, which are created by the irregular deposition, may at times drag the bottom, leading to crumpling and deformation of any sediments already deposited.[34]

CHARACTERISTICS AND ASSOCIATIONS OF THE DEPOSITS OF THE GLACIAL ENVIRONMENT. Typically glacier-deposited materials are unstratified, unsorted, and highly variable in kinds and dimensions of material. The water-deposited sediments on the stoss side of a moraine range from rapidly deposited coarse and fine material at those places where streams flowing from the ice debouch against a moraine or hill, to thin laminated clays in the various ponds and lakes formed by irregular deposition. On the leeward side of a moraine the sediments are better sorted, but range from rapidly deposited stream sands and larger particles to the finest of lake clays in the depressions without outlet. Over these lie the wind-deposited loess and the peats and marls of the succeeding swamps and lakes. The sequence may be several times repeated in greater or less perfection, usually less, due to the fact that each advance is apt to obliterate the previous deposits. All of these materials dovetail in an intimate manner.

The clays and silts of the glacial lakes may be varved. The lower part of the varve of each year is usually characterized by coarser grain and lighter color; the upper part has finer grain and darker color. The lower part is also thicker. This part represents summer deposition. A varve may con-

[35] Walther, J., Das Gesetz der Wüstenbildung, 4th ed., 1924, pp. 393 ff.

[34] Sayles, R. W., Seasonal deposition in aqueo-glacial sediments, Mem. Mus. Comp. Zool., vol. 47, no. 1, 1919, pp. 19–20.

sist of clay and silt in various proportions, almost exclusively of silt, or almost exclusively of clay. If the materials are coarse, the summer part will be relatively thick as compared to the winter part. The winter parts remain almost equally thick from year to year, so that variations in thickness of varves are largely due to variations in thickness of the summer parts. Each varve tends to be sharply distinguished from the preceding and succeeding, but in some cases varves are distinguishable with difficulty. Summer parts pass gradually into those of winter. Varved clays are without macroscopic fossils, this probably being due to the low temperatures of the waters in the glacial lakes. If the waters of glacial lakes or other places of melt-water discharge are such as to flocculate the sediments rapidly, varves do not form. Hence, they are not likely to be found in marine waters into which melt waters discharge.[35]

Deposits of the glacial environment ordinarily range from white to gray to gray-blue, but original colors of the rock particles tend to be controlling factors, and thus any color is possible, as exemplified by the red glacial clays of northern Wisconsin and Michigan. The sandy and silty parts of varved clays range from white to gray. As the fineness of the clays increases the colors tend to become darker and range from dark gray and blue-gray to red and black. However, in some instances fine clays are light colored.

The thickness of the deposits of the glacial environment perhaps may reach 1000 to 2000 feet; ordinarily the thickness is of an order of magnitude of a few hundred feet. There is great variation, and locally the deposits may be entirely wanting.

Glacial deposits contain decomposed materials only to the extent that the sources from which they were derived had undergone weathering. The consequence is that there is little leaching of fine-grained sediments.

Proof of the glacial origin of a deposit requires that the entire set-up be present, that is, the unstratified heterogeneous mixtures of coarse and fine particles bordered laterally by and dovetailing into the stratified deposits of kames, lakes, and outwash.

The surface on which glacial deposits rest is locally striated, and some of the larger particles may show striations and have one or more sides flattened or soled.[36] It must not be assumed, however, that striated particles are proof of the glacial environment or that they are particularly common in glacial sediments. Striated rock floors are more common and at the same time are better evidence of the one time existence of the glacial environment.

[35] Antevs, E., Retreat of the last ice sheet in eastern Canada, Mem. 146, Geol. Surv. Canada, 1925. This work contains an excellent bibliography. For work on varved sediments since 1925 the summaries by Antevs in the Reports of the Committee on Sedimentation should be consulted.

[36] Tarr, R. S., and Martin, L., Alaska glacial studies, 1914.

Glacial Deposits in the Geologic Column. The most ancient known glacial deposits are those of the Pre-Cambrian. The lower Huronian of the Cobalt region of Canada contains the Gowganda formation which was assigned by Coleman to deposition in the glacial environment.[37] Miller recognized the same possibility.[38] A succinct summary of the facts relating to this conglomerate was given by Collins.[39] It is described as essentially similar to conglomerates which are of known glacial deposition. Striated and soled rock particles are present, and they seem clearly not to be due to deformational processes; boulders of large size occur miles from the nearest source; the underlying surface is striated in places; and the laminated graywackes associated with the conglomerate are like, and hold relations similar to, those existing among the lake clays, outwash clays, and morainal materials in the Pleistocene glacial deposits. The only known environment in which a concurrence of all of these characters obtains is the glacial, and the Cobalt series (of which the Gowganda formation is the basal unit) compared to the Pleistocene glacial and genetically associated deposits has members which are equivalent.[40]

An ancient tillite with striated boulders and a thickness of 150 to 500 feet was found by Willis and Blackwelder in the Yang-tse Canyon of China beneath marine strata of probably Middle Cambrian age,[41] and Pre-Cambrian tillites with striated boulders extend in south Australia over an area of 460 miles from north to south and 250 miles from east to west and with a thickness of 1500 feet.[42] Pre-Cambrian tillites have been described by Blackwelder in the Rocky Mountains region.[43]

[37] Coleman, A. P., Rept. Ontario Bureau Mines, vol. 14, pt. iii, 1905, p. 127; A lower Huronian ice age, Am. Jour. Sci., vol. 23, 1907, pp. 187–192; Glacial periods and their bearing on geological theories, Bull. Geol. Soc. Am., vol. 19, 1908; The lower Huronian ice age, Jour. Geol., vol. 16, 1908, pp. 149–158; The lower Huronian ice age, Compt. Rendu, Internat. Geol. Cong., 1912, pp. 1069–1072; Ice ages, recent and ancient, 1926, pp. 220–240. This book should be consulted for data relating to deposits of the glacial environment.

[38] Miller, W. G., Rept. Ontario Bureau Mines, vol. 14, pt. ii, 1905, p. 41.

[39] Collins, W. H., Onaping map-area, Mem. 95, Geol. Ser. no. 77, Geol. Surv. Canada, 1917, pp. 82–84.

[40] Wilson, M. E., Kewagama Lake map-area, Quebec, Mem. 39, Geol. Ser. no. 55, Geol. Surv. Canada, 1913, pp. 88–98.

[41] Willis, B., and Blackwelder, E., Research in China, Publ. 54, pt. i, Carnegie Inst. of Washington, 1907, pp. 264–269; Schuchert, C., Climates of geologic time, Publ. 192, Carnegie Inst. of Washington, 1916, pp. 293–295.

[42] David, T. W. E., Rept. Ninth Meeting, Australasian Assoc. Adv. Sci., 1903, pp. 199–200; Glaciation in Lower Cambrian, possibly in pre-Cambrian time, Compt. Rend., Internat. Geol. Cong., Mexico, 1906, pp. 271–275, 275–298. Howchin, W., Rept. South Australian Glacial Investigation Committee, Rept. Ninth Meeting Australasian Assoc. Adv. Sci., vol. 30, 1906, pp. 227–262 (228–234); Glacial beds of Cambrian age in South Australia, Quart. Jour. Geol. Soc. London, vol. 64, 1908, pp. 234–263; Australian glaciations, Jour. Geol., vol. 20, 1912, pp. 193–227.

[43] Blackwelder, E., Bull. Geol. Soc. Am., vol. 37, 1926, pp. 627–631.

With the exception of the Pleistocene glacial deposits, those of the geologic past best known are of Permian age. These have been observed in South Africa,[44] Australia,[45] India,[46] South America,[47] and North America.[48]

In South Africa the glacial deposits constitute the Dwyka conglomerate with a thickness up to 1000 feet and great areal extent. The Dwyka ice sheet appears to have had an east-west extent of 600 miles and to have advanced poleward about 500 miles from an apparent source on the southern border of the Tropics. The associated deposits are of continental origin. In Australia Permian glacial formations are interstratified with marine beds. The Permian glacial deposits of India form the Talchir tillite. Associated sediments are non-marine.

Extensive glacial deposits of Cretaceous age have recently been described from central Australia. The area covers about 40,000 square miles. Rocks foreign to the region are present in the Winton series of Cretaceous age, and the supposed tillite is overlain by plant-bearing Tertiary strata. The rock particles range from a few inches to 5 feet in diameter. Most are rounded; a few are angular; water distribution is said not to be possible.[49] Eocene tillites have been described from Colorado[50] and from British Columbia.[51]

Sediments referred to a glacial origin have been described from other portions of the geologic column,[52] and it is not improbable that they may have local occurrence in the rocks of every system.

[44] Davis, W. M., Observations in South Africa, Bull. Geol. Soc. Am., vol. 17, 1906, pp. 401–415; Schwarz, E. H. L., The three Paleozoic ice ages of South Africa, Jour. Geol., vol. 14, 1906, pp. 683–691.

[45] David, T. W. E., op. cit.; Howchin, W., op. cit.

[46] Koken, E., Indisches Perm und die Permische Eiszeit, Neues Jahrb. f. Min., Festband, 1907, pp. 446–546.

[47] White, D., Permo-Carboniferous climatic changes in South America, Jour. Geol., vol. 15, 1907, pp. 615–633; Woodworth, J. B., Geological Expedition to Brazil and Chili, 1908–09, Bull. Mus. Comp. Zool., vol. 56, 1912, pp. 46–82.

[48] Sayles, R. W., and La Forge, L., The glacial origin of the Roxbury conglomerate, Science, vol. 32, 1910, pp. 723–724.

[49] Woolnough, W. G., and David, T. W. E., Cretaceous glaciation in Central Australia, Quart. Jour. Geol. Soc., vol. 82, 1926, pp. 332–350.

[50] Atwood, W. W., and Atwood, W. R., Gunnison tillite of Eocene age, Jour. Geol., vol. 34, 1926, pp. 612–622; Atwood, W. W., Eocene glacial deposits in southwestern Colorado, Prof. Paper, 95–B, U. S. Geol. Surv., 1915.

[51] Drysdale, C. W., Mem. 56, Geol. Surv. Canada, 1911, pp. 65, 95.

[52] Schuchert, C., Climates of geologic time, Publ. 192, Carnegie Inst. of Washington, 1916, pp. 263–298; Keith, A., Cambrian succession of northwestern Vermont, Am. Jour. Sci., vol. 5, 1923, pp. 118–122, 134–135; Kirk, E., Paleozoic glaciation in southeastern Alaska, Ibid., vol. 46, 1918, pp. 511–515; Shepard, F. P., Possible Silurian tillite in southeastern British Columbia, Jour. Geol., vol. 30, 1922, pp. 77–81 (glacial origin abandoned, Ibid., vol. 34, 1927). For complete consideration of the occurrence in the geologic column of deposits of the glacial environment, Coleman's "Ice Ages," 1926, should be consulted.

FLUVIAL ENVIRONMENTS

Fluvial environments are those in which flowing water is the most important agent of deposition. The environment is possible of division into three phases: the piedmont, the valley-flat, and a part of some deltas. The last is considered in connection with the delta environment. The valley-flat environment consists of the channel and the flood plain, the former shifting through the latter. Under conditions of extensive aggradation, such as those in Tertiary times over extensive areas east of the Rocky Mountains and at present in some of the more or less arid basins of western United States, valleys may disappear, and a part of the area of a stream's course may assume the aspect of a huge fan. This also is included in the valley-flat environment although it has many of the characters of the piedmont. There is no sharp division between the piedmont and the valley-flat, one passing gradually into the other. The processes on the subaerial parts of a delta are fluvial, but there is the occasional entrance of marine or lacustrine agents. Here again, there is no sharp separation.

The Environment and Sediments of the Piedmont

The piedmont environment is about the bases of highlands[53] and in intermontane valleys where accumulate creep, talus, rain-wash, rock-stream, alluvial fan and cone, and mud-flow deposits, all of these going to form the piedmont. Landslides may also make contributions; usually these are confined to mountain valleys. Great development of deposits of this environment is favored by steep slopes, marked relief, freezing weather in the highlands, and aridity and subsidence about the bases. The areas of deposition may extend for many miles from the highlands.

The surface of a piedmont deposit slopes more or less gently from the highlands. Over the higher areas the slopes may approximate the angles of repose for the materials. With distance from the highlands the slopes flatten, but on a typical piedmont they range from 4° or 5° to 15° or more. Depressions and ridges may occur, the former the channels of streams. On piedmonts in process of dissection the depressions may be wide and deep. On aggrading piedmonts the places of stream flow may be higher than inter-stream areas (fig. 116).

Characteristics and Associations of the Deposits of the Piedmont Environment. Adjacent to the bases of highlands the deposits have poor stratification and sorting, the materials having been more or less indis-

[53] The term highland is relative, as deposits of piedmont characteristics accumulate about the foot of any steep slope. It is only about the feet of highlands of considerable magnitude that the deposits are large enough to merit separate consideration.

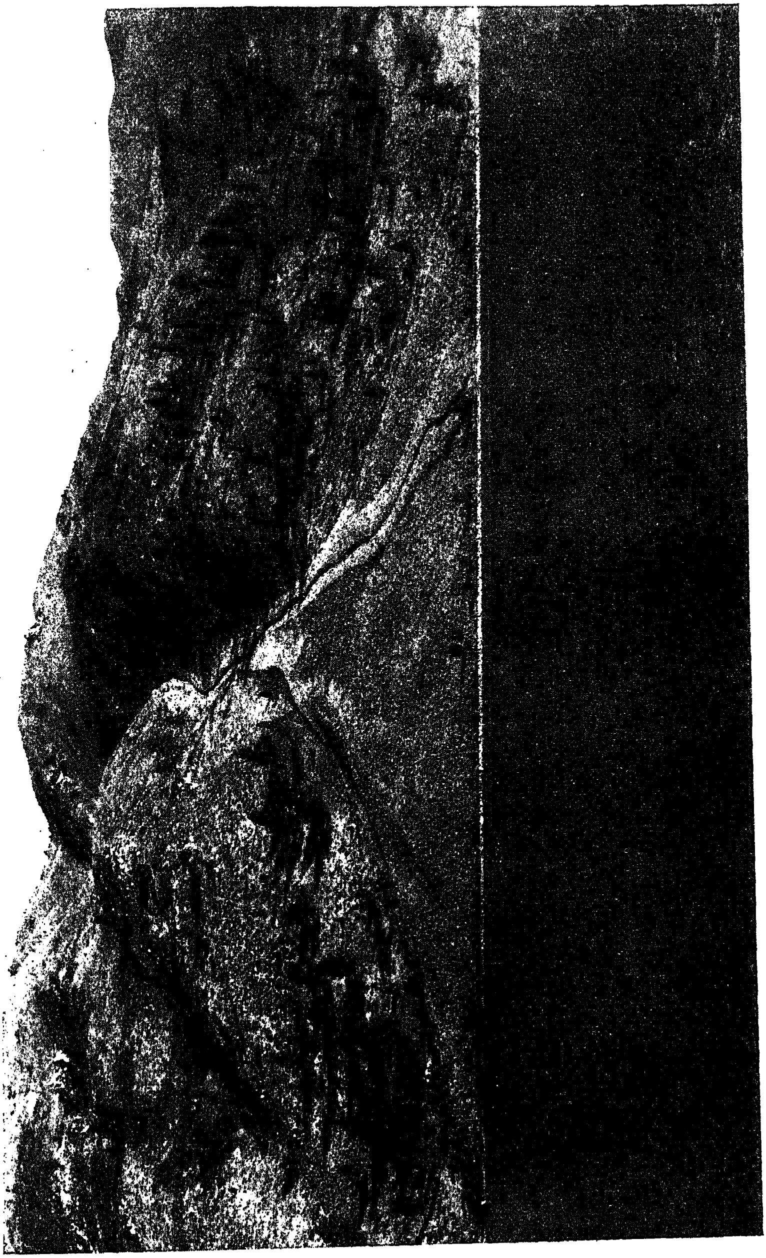


Fig. 116. An Alluvial Fan Showing New and Old Mud-flow Welts

The angle of the fan is 19°. Upper Twin Lakes, Bridgeport Quadrangle, California. Photograph by Eliot Blackwelder.

criminately piled together by torrential streams, sheet floods, mud flows, rock slides, and creep. Some of the blocks are of large dimensions. A cloudburst in the San Gabriel Mountains of southern California carried blocks up to about 17 tons weight for a distance of a quarter of a mile.[54] Organic matter is relatively scarce and, as transportation is short, the rock fragments are little rounded. With distance from the highlands the poorly stratified deposits grade into others of more regular stratification. Still farther distant the deposits pass insensibly into those of the valley-flat environment.[55]

Small basins may form on a piedmont surface through the colaescence of two fans along their lower outer margins. Small lakes and swamps may develop in these depressions and form deposits dovetailing with typical deposits of the piedmont environment. Some eolian deposition may also occur upon the fans. The stream deposits are deposited at relatively high inclinations, and they are likely to be considerably cross-laminated, with inclinations in the same general direction. Mud cracks may develop in suitable sediments. Highlands with glaciers contribute a volume of gravels to the fans and cones which is much greater than where such are not present; the deposits may then have some characteristics of those formed fluvio-glacially.

The colors of piedmont deposits vary somewhat with the climate, but the colors of the composing rocks exert a large influence. Most of the sediments are gray or yellow, but there may be red and brown colors. Local accumulation of sufficient organic matter may give dark colors.

The rocks which result from deposition in this environment are conglomerates, sandstones, arkoses, graywackes, and shales. The aggregate is best designated as a fanglomerate.[56] There are no original limestones, ferruginous deposits, salt, or gypsum, and little carbonaceous material. However, some of the deposits may be entirely composed of limestone, flint, etc., depending upon the character of the rocks from which the sediments come.

The thickness of deposits which accumulate in the piedmont environment may be very great. With stationary crust one or two thousand feet appears possible, but as many piedmont accumulations seem to be in regions subject to periodic downfaulting or synclinal warping, and the sources of the sedi-

[54] Wolff, J. E., Cloudburst of San Gabriel Peak, Los Angeles County, California, Bull. Geol. Soc. Am., vol. 38, 1927, pp. 443–450.

[55] An historical summary and bibliography of studies relating to fluvial deposits is that of Professor A. C. Trowbridge, Rept. Comm. on Sedimentation, 1928–29, 1930, Nat. Research Council.

[56] Lawson, A. C., The petrographic designation of alluvial-fan formations, Bull. 7, Univ. California Publ., Dept. Geol., 1913, pp. 325–334.

ments appear to be in regions of uplift, it is possible for many thousands of feet to accumulate.

Piedmont deposits usually do not contain much organic matter because of the torrential nature of deposition and the high porosity of the composing materials. However, floods due to cloudbursts may overwhelm the entire surface of a piedmont and produce great destruction of such life as is present. A large quantity of organic matter may thus be entombed and preserved.

In general, deposits of the piedmont environment are rudely stratified or without stratification; stratified beds have high initial inclinations and are considerably cross-laminated; fine sediments may be mud cracked; channeling is locally common; occasional beds of shale are present; particles should range from very small to blocks of large dimension; fossils should be generally absent; and colors tend to be largely determined by the character of the composing rocks. There is a dovetailing of gravels, sands, silts, and clays, or the indurated equivalents.

The following criteria suggested by Trowbridge and amended after him may serve to distinguish piedmont deposits from those of other environments:[57]

1. The range in dimension of particles is from very small to boulders 30 feet in diameter. Particles are more or less slightly shaped by water.
2. The coarse material has wide but irregular distribution.
3. The materials tend to be homogeneous lithologically because of local derivation.
4. The deposits are not well stratified or sorted and grade in one direction into essentially unstratified deposits and in the other into the better stratified deposits of the valley-flat environment. Stratified, partly stratified, and thoroughly unsorted materials are present in more or less equal proportions.
5. Stratification planes have inclinations up to 16° to 18° and have fan-like arrangement.
6. The stratification is of the lens and pocket type and never in uniform continuous layers. Stratified units extend but short distances.
7. Fossils are not common. Those present are of types related to the environment.
8. Particles may have experienced some decomposition but they are largely the result of some form of rock breaking.
9. Colors tend to be yellow and gray, colors of the composing rocks being the determining factors.
10. Materials become finer with distances from the uplands.

THE PIEDMONT CYCLE. The piedmont cycle is as follows: The sediments begin to accumulate near the base of the upland where the change to a more gentle slope decreases competency and capacity to the extent that deposition results. Subsequent deposition takes place upon and inward and outward from the initial deposits, the sediments thus rising on the upland slopes and

[57] Trowbridge, A. C., The terrestrial deposits of Owens Valley, California, Jour. Geol., vol. 19, 1911, pp. 706–747.

extending outward over the bordering plains or lowlands. In course of time deposition over a piedmont comes to an end and is succeeded by erosion. The deposits are then removed in somewhat reverse order to their development, that is, the deposit is lowered and its margins retreat toward the place or places of initial deposition.

EXISTING DEPOSITS OF THE PIEDMONT ENVIRONMENT. The present extent of piedmont deposits is very great on the flanks of the great highland regions of the world, particularly those bordering great arid regions. According to Barrell,[58] the extent of these deposits in western United States, Argentina, and Italy may be considered roughly equal in area to those portions of the lofty mountains from which they come, but some deposits belonging to the valley-flat environment may be included in this estimate. The piedmont or bajada[59] deposits along the east foot of the Sierra Nevada are fairly typical. The streams enter the fans on the apices and may or may not follow the axes. The stream depressions range to about 40 feet deep and less than 100 feet wide; average maximum depths are 20 to 25 feet. The composing sediments consist of material derived from the granitic rocks of the Sierras and are products of immature weathering. The components are pieces of rocks rather than individual minerals. The dimensions of particles range from very small to large, one 10 by 20 by 30 feet above ground with an unknown extent beneath the ground being known. This boulder is at least $1\frac{1}{2}$ miles from its source and probably reached its present position as a part of a mud flow. The deposits are stratified into a series of radiating lenses of which no one has great extent; sorting is extremely poor and lenses of coarse material lie laterally and vertically with others of fine material.[60]

Piedmont deposits of the Cucamonga district of California are more than a thousand feet thick and still growing, the materials consisting of boulders, cobbles, gravels, sand, and silts, all poorly sorted and indistinctly bedded.[61] Sizes of particles decrease rapidly away from the apices of the fans. The process of the building of a fan was illustrated by a flood on February 16, 1927. The flood waters flowed in shallow channels cut below the general surface. As these waters spread, a part of their load was dropped, thus lessening the grade above and steepening it below. This increased the deposition of sediments with the result that a low dam was built across the channel. This dam divided or diverted the waters, and the process was

[58] Barrell, J., Relative geologic importance of continental, littoral, and marine sedimentation, Jour. Geol., vol. 14, 1906, p. 332.

[59] Tolman, C. F., Erosion and deposition in the southern Arizona bolson region, Jour. Geol., vol. 17, 1909, p. 141.

[60] Trowbridge, A. C., op. cit.

[61] Eckers, R., Alluvial fans of the Cucamonga district, southern California, Jour. Geol., vol. 36, 1928, pp. 224–247.

repeated at some other place in the current. Orange groves cover parts of the upper or mountain portions of the fans of the Cucamonga district and thousands of tons of boulders have been removed in order to concentrate sufficient fine materials for cultivation. In some places the boulders are so numerous as to make cultivation essentially impossible.

Parts of the Sespe formation (Tertiary) of California have been interpreted as of alluvial fan origin.[62] The Overton (Tertiary) fanglomerate of Nevada varies in thickness from 20 to more than 3,000 feet.

> Average and maximum sizes of fragments range between wide limits. . . . Heavy beds are made of fragments 4 to 24 inches in diameter, small pieces occurring only in the interstices. Boulders 3 feet through are common, and one remarkable layer has numerous masses of Kaibab limestone 10 to 30 feet in greatest dimension. . . . Among the smaller boulders and pebbles sharp angularity is not uncommon, but as a rule the fragments are subangular, and a small percentage of the pebbles are well rounded. . . . Nowhere is there more than the slightest approach to sorting. Evidence of pulsation in deposition is general, the fragments in each thick layer averaging coarser at the base than at the top, but in all beds pebbles and boulders of various sizes are jumbled together, their long axes trending in all directions, though they show a tendency to parallel the bedding. In places many large boulders are banked together, with little finer material between them, but as a rule the matrix of pebbles, sand, and cement envelops each boulder. Some boulders of the largest size occur isolated in a matrix of small pebbles and sand. In a large way bedding planes are regular and parallel, but in detail irregularity is extreme, lenses everywhere interfingering. Thick narrow lenses of sand essentially free from pebbles occur, but they are exceptional in this phase of the formation.[63]

Tertiary piedmont deposits occur in other parts of the Pacific Coast states and about other mountain areas of the west, and much of the Tertiary along the east front of the Rocky Mountains was deposited in this environment. Parts of the Molasse and Flysch of the Alps and the mountainward portion of the Siwalik[64] formation of India originated under piedmont conditions. The Triassic Newark series throughout its distribution from Nova Scotia to North Carolina has piedmont deposits over extensive areas along the margins of the basins of accumulation,[65] and such seem to have development in the various Old Red Sandstone areas of the British Isles.

[62] Kew, W. S. W., Bull. 753, U. S. Geol. Surv., 1924, p. 30; Reinhart, P. W., Origin of the Sespe formation of South Mountain, California, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 743–746.

[63] Longwell, C. R., Geology of the Muddy Mountains, Nevada, Bull. 778, U. S. Geol. Surv., 1928, pp. 68–74.

[64] Oldham, R. D., Geology of India, 1893, pp. 315, 356, 465; Pilgrim, G. R., Correlation of the Siwaliks, Rec. Geol. Surv. India, vol. 43, pt. i, 1913, pp. 264–326; Weller, J. M., The Cenozoic of northwest Punjab, Jour. Geol., vol. 36, 1928, pp. 368–369.

[65] Davis, W. M., The Triassic formation of Connecticut, 18th Ann. Rept., pt. ii, U. S. Geol. Surv., 1898, pp. 9–192; Kummel, H. B., The Newark rocks of New Jersey and New York, Jour. Geol., vol. 7, 1899, pp. 23–52; Reynolds, D. D., and Leavitt, D. H., A scree of Triassic age, Am. Jour. Sci., vol. 13, 1927, pp. 167–171.

In older systems piedmont deposits are: parts of the Keweenawan conglomerates of the Lake Superior region, the Doré series of western Ontario,[66] parts of the Great Smoky and Cochran conglomerates of the Ocoee and Chilhowee groups of the southern Appalachians,[67] some of the Pennsylvanian sediments of the Appalachians, and considerable parts of the New Glasgow conglomerate of northern Nova Scotia.[68] It can hardly be doubted that many systems have the deposits of the piedmont environment in as extensive development as is the case at the present time.

Environment and Sediments of the Valley-flat

The valley-flat environment is that of the channels and flood plains. The two are very unlike in conditions and in sediments, but there are such intimate relationships between them that separation is not possible. In this environment there is considerable stability of stream position as opposed to the rather general instability over a piedmont. Under conditions of extensive aggradation, however, a valley may become completely filled and disappear. Valley-flats are likely to have many lakes and swamps, features which ordinarily are not present on a piedmont.

The deposits of the valley-flat differ from those of the piedmont in greater lithologic diversity, lesser range of dimension and more extensive transportation of particles, greater degree of modification of sediments, somewhat different methods of deposition, different sedimentary structures, much better sorting and stratification, absence or scarcity of large fragments, and greater abundance of organic matter.

An environment may be considered valley-flat and not piedmont if the stream is situated in a valley, possesses a channel of fairly fixed position as opposed to one that is constantly changing, and has the channel bordered by a flood plain. As previously noted, however, the distinction does not always hold. The environment may be considered deltaic if the flat land near the mouth of a stream developed through building outward by stream deposition into the body of water into which the stream empties, and which is still more or less subject to invasions by that body of water. The distinctions of the valley-flat environment from those of the piedmont and delta are in position, relations to other deposits, and character and structure of the deposits.

[66] Collins, W. H., Quirke, T. T., and Thomson, E., Michipicoten iron ranges, Mem. 147, Geol. Surv. Canada, 1926, pp. 22–23.

[67] Barrell, J., Nature of the Lower Cambrian sediments of the southern Appalachians, Am. Jour. Sci., vol. 9, 1925, pp. 1–20.

[68] Young, G. A., Guide Book, no. 1, pt. ii, 12th Internat. Geol. Cong., 1913, pp. 229–239. Coleman assigns the New Glasgow conglomerate to a glacial origin, Late Paleozoic climates, Am. Jour. Sci., vol. 9, 1925, p. 200.

Deposition upon any part of the valley-flat and in any part of a channel is determined by the rate of supply from a stream's headwaters and by what is occurring downstream from the particular place. The deposition of sediments over a delta will compel deposition upstream. Rise of sea level will submerge mouths of streams, compelling deposition upstream. Any increase in volume of sediments from the regions of supply is likely to increase deposition in stream channels and ultimately over the flood plains. Decrease in supply may replace deposition by erosion. Fall of sea level may do the same thing.

CHARACTERISTICS AND ASSOCIATIONS OF THE DEPOSITS OF THE VALLEY-FLAT ENVIRONMENT. The deposits of the valley-flat environment, as has been said, are formed in the channels and on the flood plains. The latter deposits are made during floods over many parts of the flood plain, in flood-plain lakes and swamps, and under certain climatic conditions there may be dune and other wind deposits such as obtain at the present time over parts of the flood plains of the Platte River of Nebraska, the Arkansas River of Kansas and Oklahoma, and elsewhere.[69] Deposits of the valley-flat environment appear to have their greatest development during the mature and later stages (not extreme old age) of the erosion cycle.

The nature and color of flood-plain deposits depend largely on the sources of the sediments, the climatic and topographic conditions at the sources, the climatic conditions over the flood plain, the duration and distance of transportation, and the extent and depth of water on the flood plain during each year. On flood plains having an abundance of vegetation it makes little difference what were the colors of the sediments at the times they were deposited, as any contained iron oxide is certain to be reduced and the sediments given gray and perhaps dark colors. On dry river plains, like the Great Plain of China, the sediments may be further oxidized, leading to greater intensity of the colors of oxidation. This may occur over parts of the flood plain of any stream, and an oxidized layer, or portion of a layer, may be found in any flood-plain deposit.

Flood-plain sediments are mainly silts and clays, but sands are common and gravels are occasional. Considerable organic matter usually is present. The deposits also contain a considerable content of soluble matter precipitated from solution following the evaporation of water contained in the sediments, or resulting from chemical or organic action. In semi-arid regions calcium carbonate, calcium sulphate, and other salts precipitated from evaporating water may be large in amount. Calcareous deposits due to evaporation, algal growths, etc., may be made in flood-plain lakes in suffi-

[69] Hill, R. T., Sand rivers of Texas and California and some of their accompanying phenomena, Abstract, Bull. Geol. Soc. Am., vol. 34, 1923, p. 95.

cient quantities to form beds of limestone. This is the case in Tertiary strata of South Dakota and elsewhere.[70]

Channel sediments consist of gravels, sands, silts, and clays.[71] They are made during all stages of a stream's history: in the deeps during slack water, when the shallows are being eroded, and on the shallows during flood water; but unless a stream is generally aggrading or migrating laterally, channel deposits are entirely ephemeral. If the conditions permit some degree of permanence to the deposits, an extremely erratic distribution of gravel, sand, silt, and clay results. The gravels show wear commensurate with the transportation and imbricate upstream.[72] All deposits are lenticularly bedded, more or less extensively cross-laminated, usually with a component of inclination downstream but with possibilities of minor cross-lamination in an upstream direction, and contain current ripple marks consistent with the directions and velocities of the currents. Wave ripple marks are rare. Sections through channel deposits show lenticular and cut and fill bedding and are replete with local unconformities of considerable relief.

The channel sediments of a stream migrating over its flood plain are deposited unconformably over an eroded surface cut on flood-plain, channel, lake, and swamp sediments. The channel sediments in turn may become unconformably overlain by others similar to those on which they rest.

The deposits made in the valley-flat environment are mainly the result of mechanical processes. Some are of organic origin, and some may arise from chemical reactions caused by the mingling of waters of different tributaries. There is much flocculation of colloids for the same reason. This seems to be obvious in the Mississippi River system below the mouth of the Missouri, due to the latter's high content of dissolved sulphates.[73]

The dense populations of plants and animals over many flood plains suggest that remains of such should occur in abundance in flood-plain sediments. The rate of accumulation, however, is ordinarily not rapid, and the major portions of the organic remains are destroyed before burial. Only in cases of floods destroying and locally burying organisms beneath thick cover is there much chance of remains being preserved. The chances are much better in flood-plain lakes, in the deposits of which shells and tests of invertebrates, skeletons and impressions of fishes, impressions of leaves, etc., may be excellently preserved.

[70] Wanless, H. R., The stratigraphy of the White River beds of South Dakota, Proc. Am. Philos. Soc., vol. 52, no. 4, 1923, pp. 191, et al.

[71] Lugn, A. L., Sedimentation in the Mississippi River between Davenport, Iowa and Cairo, Illinois, Augustana Library, Publ. no. 11, 1927, pp. 1–104. This paper gives the results of an extensive study of channel sediments.

[72] Johnston, W. A., Imbricated structure in river-gravel, Am. Jour. Sci., vol. 4, 1922, pp. 387–390.

[73] Knight, J. H., Unpublished thesis, University of Wisconsin, 1925.

Each flood season is succeeded by one of low water during which the materials of a flood plain may become thoroughly dry and crack, the extent of the cracking being determined by the character of the sediments and the duration of the drying. Subsequent wetting, either by rains or floods, produces more or less closing of cracks. The next drying leads to a reopening of old cracks or the development of new, and partial or complete obliteration of lamination and bedding may result. Organisms burrowing in the materials of the flood plain assist in this obliteration.

As flood plains contain lakes and swamps and as both change position because of deposition and migrations of streams and their tributaries, there develops a dovetailing of marls and gray and black muds of the lake environment; black muds and peats of the swamp environment; gravels, sands, silts, and clays of the channel environment; and varicolored clays and silts of the flood plain. There is a wide range in variety of sediments in different sections. As streams wander in their flood plains, particularly under conditions of aggradation, local unconformities of considerable relief are developed.

The Tertiary sediments of western Nebraska, North and South Dakota, eastern Montana and Wyoming,[74] and western Kansas excellently illustrate the characteristics of the valley-flat environment. The sediments are clays, silts, sands and sandstones, and gravels and conglomerates. The clays and silts have greenish, pink, maroon, and yellow colors; the colors of the sands and sandstones are yellow, gray, and reddish. All varieties of sediments may contain considerable lime, and this may be so abundant in the sands and gravels as to cement them into a firm rock, as is the case in the Tertiary "Mortar Beds" of Kansas and Nebraska.

Thickness of Deposits in the Valley-flat Environment. Under average conditions the deposits of the valley-flat environment are thin and ephemeral. Most streams alternately aggrade and degrade, and the sediments have but temporary lodgement. It is said that the "construction of about a square mile of new deposits, 60 feet deep, in about two months time, is an almost annual occurrence locally on the Indus."[75] The materials of these deposits have been derived from upstream where parts of previous deposits have been eroded. Most degrading streams have local base levels, and some have narrow flood plains, usually developed either through erosion or erosion followed by deposition. As channels deepen, the flood plains cease to be covered with water at any time and the composing materials there begin to be removed. Streams flowing through semi-arid regions may make deposits of great thickness therein, and a greater thickness may accu-

[74] Darton, N. H., Folios 85, 87, 88, 108, U. S. Geol. Surv.
[75] Hill, A., Erosion and deposition by the Indus, Geol. Mag., vol. 47, 1910, pp. 289–290.

mulate over a valley-flat environment where it passes over or enters a subsiding region. Where all conditions—climatic, physiographic, and diastrophic—are favorable, tremendous thicknesses may be attained, as, for instance, the present and past deposits of the Indo-Gangetic plain and the Tertiary of the states east of the Rocky Mountains.

VALLEY-FLAT DEPOSITS OF THE PAST. The Tertiary sediments of the states east of the Rocky Mountains are largely of stream deposition, and large parts were certainly deposited in the valley-flat environment.[76] Formerly these were considered to have been deposited in lakes, a view shown to be incorrect first by Haworth[77] and subsequently by Davis.[78] There is a great extent of similar deposits in the Rocky Mountain region, of which large parts, however, developed in the piedmont environment, and on the coastal plain of Texas the Reynosa formation possibly thus developed.[79] The Cretaceous formation of Kansas and southern Nebraska generally known as the Dakota was deposited in considerable part in the valley-flat environment of streams, some of which are thought to have flowed[80] from the east. The Morrison formation of Montana, Wyoming, and Colorado, with its lenticular conglomerates and sandstones and marginal clays and shales, seems best interpreted as a flood-plain and channel deposit. Associated limy beds may have been made in lakes on the flood plain. The Todilto (?) formation of Gilluly and Reeside has characters indicating deposition on flood plains and in channels.[81] Channel deposits are present in the Pennsylvanian strata of Missouri,[82] Kansas, Kentucky, and Illinois, the channels having been cut in marine and delta sediments. The materials are mainly sandstones, but there is considerable shale, some conglomerate, and a little coal. The sandstones have brown, red, and gray colors and are more or less cross-laminated. Some are firm and massively bedded; others are thin-bedded and poorly cemented. The particles of the conglomerates are mainly composed of limestone in Missouri and of vein quartz in Kentucky, and range up to several inches in diameter. Some are rounded; others are

[76] Ward, F., The geology of a portion of the badlands, Bull. 11, South Dakota Geol. Nat. Hist. Surv., 1922; Wanless, H. R., op. cit.

[77] Haworth, E., Physical properties of the Tertiary, vol. 2, Kansas Geol. Surv., 1897.

[78] Davis, W. M., Continental deposits of the Rocky Mountain region, Bull. Geol. Soc. Am., vol. 11, 1900, pp. 590–604.

[79] Trowbridge, A. C., Reynosa formation in lower Rio Grande region, Bull. Geol. Soc. Am., vol. 37, 1926, pp. 445–462.

[80] Rubey, W. W., and Bass, N. W., The geology of Russell County, Kansas, Bull. 10, pt. i, Kansas Geol. Surv., 1925, pp. 54–62.

[81] Gilluly, J., and Reeside, J. B., jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah, Prof. Paper 150, U. S. Geol. Surv., 1928, pp. 70–72.

[82] Hinds, H., and Greene, F. C., The stratigraphy of the Pennsylvanian series of Missouri, Missouri Bur. Geol. Mines, 1915, pp. 91–106.

angular. The Pleistocene and Recent deposits of the Indo-Gangetic plain consist of gravels, sands, silts, and clays of unknown, but great thickness. At Lucknow a well was drilled in these deposits to a depth of 1336 feet without finding a rock floor or marine deposits.[83] The sediments contain many concretionary masses of lime carbonate, known as kankar,[84] and in some places the carbonate serves as a cement for other sediments. Nodules of pisolitic limonite are not uncommon. To the north of the plain deposits are those of the Siwalik formations consisting of clays, sandstones, and conglomerates with a thickness of 16,000 to 20,000 feet. As previously noted, great parts of these were deposited in the piedmont environment.

The Great Plain of China is underlain by fluvial deposits of unknown, but probably great thickness. These sediments contain an occasional marine layer on the coastal side, they are strongly oxidized, and when consolidated will probably give rise to a series of red beds. Grabau has recently presented the view that the "normal graptolite shales," consisting of thin layers of black mud intercalated between thicker beds of coarser sediments, were deposited on a river plain similar in relief to the Great Plain of China, the beds bearing the graptolites representing occasional inundations of the sea.[85]

It is the view of Kiaer[86] that the Downtonian sandstones of Norway were deposited over flood plains, and their lithological characters and the spotted distribution of the organic remains are in harmony with this interpretation. It seems probable that parts of the Ocoee and Chilhowee series of the southern Appalachians[87] originated in the valley-flat environment, and parts of the Keweenawan of the Lake Superior region had a like origin.

THE PALUDAL (SWAMP) ENVIRONMENT AND ITS SEDIMENTS

Swamps develop in regions of immature topography, on the deltas and flood plains of rivers, along the coasts of lakes and the ocean; and under the climatic conditions of high relative humidity and regular and abundant rainfall they may form on almost any surface. Vegetation usually covers the entire surface of swamps, although some of it may be beneath water. In most swamps the plants are not of large size, but some, as the cypress swamps of southern United States, support large trees. Except in the shallow

[83] Oldham, R. D., Geol. of India, Geol. Surv. India, 1893, p. 432.

[84] Oldham, R. D., op. cit., pp. 436–437; called kunkar by Reed, F. R. C., Geology of the British Empire, pp. 61, 144.

[85] Grabau, A. W., Origin, distribution, and mode of preservation of the graptolites, Mem. Inst. Geol., Nat. Res. Inst. China, no. 7, 1929, pp. 1–52.

[86] Kiaer, J., The Downtonian fauna of Norway, Vidensk. Skrifter, Mat. naturv. Klasse, no. 6, 1924, pp. 1–15.

[87] Barrell, J., Nature and environment of the Lower Cambrian sediments of the southern Appalachians, Am. Jour. Sci., vol. 9, 1925, pp. 1–20.

pools and sluggish stream channels, the sediments undergo little reworking after their first deposition other than that due to organisms.

Distribution and Classification of Swamps

Existing swamps have their greatest development in polar temperate latitudes. Two factors are responsible: one climatic, due to small evaporation in relation to rainfall, the other topographic, due to the immature topography resulting from Pleistocene glaciation. There are extensive swamps in tropical and subtropical latitudes. Examples are those of Florida,[88] Virginia and the Carolinas,[89] the Amazon Valley, Sumatra, Brahmaputra delta, Central America, etc.

In North America swamps abound over the glaciated areas, where both topographic and climatic conditions are favorable, and on the Atlantic-Gulf-Mississippi coastal and delta plain. It has been estimated that the area of swamp land in the United States approximates 100,000 square miles.[90]

Swamps may be classified as follows:

- Marine (paralic) swamps or marshes
  - Grass and reed swamps (salt marshes)
  - Mangrove swamps
- Fresh-water swamps
  - Swamps connected with basins
    - Lake swamps
    - River swamps
  - Swamps on flat or gently sloping surfaces, terrestrial bogs.

MARINE SWAMPS OR MARSHES. Marine swamps or marshes represent a mixed continental and marine environment and usually begin their development in a protected part of the shallow-water zone, which may have been produced by the development of an off-shore barrier beach, by spits and bar between two headlands, by emergence of a sea bottom, or by submergence of a land area. In tideless seas, or those in which the tides are small, the development of barrier beaches and bars is not so essential as in the open ocean, and many shallow bays become marine marshes without the intervention of a protecting barrier.

The history of a marine swamp formed behind a barrier has been stated

[88] Harper, R. M., Preliminary report on the peat deposits of Florida, Geol. Surv. Florida, Third Ann. Rept., 1910, pp. 197–366.

[89] Davis, C. A., Preliminary report of peat deposits in North Carolina, Economic Paper 15, North Carolina Geol. Surv., 1908, p. 151.

[90] Shaler, N. S., General account of the fresh-water morasses of the United States with a description of the Dismal Swamp district, 10th Ann. Rept. U. S. Geol. Surv., 1890, pp. 261–339 (264).

to be as follows:[91] Prior to the building of the barrier the environment is marine (in some cases lacustrine), and the sediments are of that origin. After the building of the barrier, quiet water prevails behind it, and the deposition of sediments continues as before except that they may be finer and may be deposited in brackish and at times fresh water. When the water becomes sufficiently shallow, eel grass takes possession and develops submerged meadow-like areas. These shelter numerous animals and filter sediments from the water, and ultimately the bottom is built to above mean tide. Grass and reed plants adapted to the conditions take possession. These plants have xerophytic structures and are typified by such species as *Spartina glabra* and *S. patens*. The former grows nearer the water, attains a maximum height of 6 feet, and has thick underground stems with long, much branching roots. *S. patens* is a more grass-like plant.

The different plants capture sediments brought into the swamps from the land and from the sea, storm waves bringing in gravel, shells, sands, and muds. Gravel is not common; the others are, and the shells usually are small. If dunes are in the vicinity, considerable wind-deposited material may be carried into the swamps. The quantity of inorganic matter brought to a swamp during this portion of its history is large and ordinarily exceeds that of organic origin.[92]

Tidal waters (if tides are present) flow inward and outward through marine swamps in tortuous channels. As the outward flow generally is rapid and the materials of a swamp are easily eroded, considerable quantities of vegetable matter may be carried to deeper waters. Such sediments in the eastern Baltic near Hapsal are carried 6 to 8 miles from the swamp. Ultimately, however, the accumulations of materials build the swamp above salt-water level; fresh waters invade the accumulations; and fresh-water plants take possession. Since the accumulations may settle, there is a possibility of a return of salt water conditions.

A history as outlined could obtain only in a region of stationary strand-line. If slow submergence occurred, any phase of the building might be long continued; if emergence, any stage would be much abbreviated. Rapid, but intermittent submergence might repeatedly bring the swamp below the eel-grass level, and thus marine and swamp sediments might be many times repeated.

In the marshes of the east Baltic reed-like plants grow to the seaward edge of the swamps on surfaces consisting of soft mud. They reach a maximum height of 7 to 8 feet. On the land margin the plants are more grass-like,

[91] Davis, C. A., Salt marsh formation near Boston and its geological significance, Econ. Geol., vol. 5, 1910, pp. 623–639.

[92] Davis, C. A., op. cit., p. 631.

and the ground is firm. Shallow pools of brownish colored water occur locally, and the muds are highly impregnated with hydrogen sulphide.

The salt marshes of Norfolk, England, have

> the lowest and always submerged parts of the inlets . . . either practically bare or show a luxuriant growth of marine algæ, especially *Fucus*. At the next higher level different plant assemblages are found which are not necessarily constant along the same level. Frequently the first stage above the Fucus zone is typified by species of *Salicornia* (Marsh Samphire or Glasswort) and of *Suæda maritima* (Seablite). In some places, notably on soft mud and at a somewhat lower level, *Zostera marina* and *Z. nana* (Grasswrack or Wigeon-grass) are met with, and are often associated with various algæ. All these lower marshes are covered by every high tide. There is a transition to higher levels, and *Salicornia* gradually gives place to other plants such as *Glyceria maritima* (Salt-marsh Grass) and *Trilochin* sp. (Sea-arrow Grass), or *Aster tripolium* (Sea-aster). These are succeeded upward by *Limonium* spp. (Sea-lavender), *Plantago maritima* and *P. coronopus* (Sea-plantains), *Spartina* spp. (Rice-grass, etc.), *Spergularia media* (Sea-spurry), and *Armeria maritima* (Sea-thrift), though the associations are not always distinct. It cannot be emphasized too strongly that a *gradual transition* is apparent between all these various phases. The highest levels are characterized by *Juncus maritimus* (Sea-rush), *Agropyron junceum* (Jointed couch-grass), and *Artemesia maritima*, but here again the association is mixed. One other plant, *Atriplex* (*Obione*) *portucaloides*, is particularly characteristic of the Norfolk marshes. It occurs at various levels, from the *Salicornia* horizon upwards, and often spreads over large areas, becoming dominant in those places. Perhaps, the most striking thing about it is its tendency to grow along the banks of creeks, which it overhangs. As it is a thick shrubby plant, it traps a great deal of material and may raise the levels of the creek banks above the levels of the marshes as a whole.[93]

Certain plants, as *Suæda fructicosa*, are important in fixing shingle bars, and others, as *Agropyron junceum*, *Elymus arenarius*, *Arenaria peploides*, and *Ammophila arenaria* play a like function in holding dune sands bordering the marshes. In the above discussion it has been more or less assumed that bars are present, but these are not essential. On the Gulf of St. Lawrence in the broad bay between Eskimo Point and the mouth of Mingan River a salt marsh borders the sea for several miles and probably gradually passes into a fresh-water marsh inland. On Hudson Bay over long stretches between Port Churchill and Chesterfield Inlet there are areas up to 8 miles wide which are laid bare at low tide,[94] the tidal range averaging around 12 feet. Were it only a couple of feet and the climate congenial, these flats would be covered with a dense growth of salt-marsh vegetation on the outer or seaward margin and an equally dense growth of fresh-water marsh vegetation on the landward margin. Also, during times of extremely low lying lands

[93] Steers, J. A., and Thomas, H. D., Vegetation and sedimentation as illustrated in the region of the Norfolk salt marshes, Proc. Geologists' Assoc., vol. 40, 1930, pp. 341–352.

[94] Lund, R. J., Personal communication.

such as existed over the American interior during some parts of the Paleozoic, there seem to be no good reasons why marshes of tens and even hundreds of miles width may not have bordered some of the epicontinental seas. Certain conditions of depth of water, range of tides, and slope of bottom would form such extensive swamps, in which, it is suggested, were formed some of the black shale formations found in the Paleozoic sections of the American interior.

Thickness of Marine Swamp Deposits. Eel grass and most marsh plants do not begin to grow more than 10 to 12 feet below low-water level, and the deposits may not rise more than a few feet above high-tide level, so that the total thickness with stationary water level cannot be very great—the tidal range plus perhaps 20 feet as a maximum. Under conditions of submergence so slow that water level keeps pace with accumulation of organic and other débris, any reasonable thickness of deposits is possible. Such nicely balanced ratio between rise of water level and accumulation of sediment must have been not uncommon, and there must be several deposits in the geologic section which are indicative of the marine swamp environment. Such are some of the coals, and it is the writer's view that some of the dark shales poor in marine fossils formed under conditions allied to marine marshes. Some of these are measured in tens and even in hundreds of feet.

Deposits of Marine Swamps. Before the eel-grass stage the sediments of the bottom are gravels, shells, sands, muds, and organic matter of the average shallow-water environment. When the eel-grass stage is reached, the remains of these plants mingle with the sediments, and the latter may accumulate more rapidly than before due to the straining action of the vegetation. Under some conditions the sediments may be largely calcareous, and perhaps it was in this environment that developed some of the limestones and dolomites containing supposed seaweeds.[95] Grabau has suggested that the "Bird's Eye" limestone of New York is of this origin.[96] At this stage the sediments are largely inorganic, ordinarily are well stratified, and contain marine shells. When *Spartina glabra* makes its appearance, the organic matter forms a greater part of the sediments, and in the *S. patens* stage it may compose the major portion. In both *Spartina* stages the formation of hydrogen sulphide may be large, and it is probable that sulphates are reduced and sulphuric acid formed. Iron sulphide should develop at this time. Calcium carbonate should be rare because of the high solvent ability of the waters due to abundance of carbon dioxide and the

[95] Wallace, R. C., Pseudobrecciation in Ordovician limestones in Manitoba, Jour. Geol., vol. 21, 1913, pp. 402–421.

[96] Grabau, A. W., Principles of stratigraphy, 1913, p. 488

presence of sulphuric acid. The quantity of toxic products may, indeed, be so large as to make the waters unfit for animal life.[97]

The sequence of deposits of a swamp whose history is as outlined should be "sand, silt or mud at the bottom, up to about 12 feet below low water mark; between these two levels the easily recognizable remains of the eel grass mixed with the silt and the shells of mollusks and other marine organisms." Above this "should be found another layer of silty mud, up to the level above which the salt water grasses grow," where the "remains of these plants should be found in constantly increasing numbers, until they form the bulk."[98] In case of submergence or emergence there would be departures from this sequence.

Mangrove swamps are confined to warm regions, where they extend the mainland seaward and initiate the formation of islands. They build new land as follows:[99]

> Behind the keys, in the regions of slack water, deposition of sediment is taking place, forming banks of calcareous ooze. After these shoals have been built to within a foot of water level (at low tide), young mangroves begin to catch and grow. . . . The plants become still more numerous, further increase in size, and ultimately form a mat of interlocking roots and branches resulting in keys. When the plants become thick they catch and retain sediment and ocean drift. . . . After a time, whether it be a newly formed key or the margin of a land area, the mangroves . . . form land, and thus cut off their roots from the necessary supply of sea water, causing their own death. The land surface then acquires another vegetation. But the marginal fringe of mangroves persists to protect the young island from the erosive action of the ocean waves, and young mangroves spread seaward to add new land to that already formed.

FRESH-WATER SWAMPS. Fresh-water swamps develop on flat and gently sloping areas and in connection with basins. The former require climatic conditions which keep the surface generally moist. The basins usually contain water, but they may be dry for parts of each year. Fresh-water swamps are also sequential to marine swamps and there probably attain their greatest extent.

Some flat-area swamps have large trees, and others are covered with low bushes. The alder is representative of the latter; the black spruce, tamarack and cypress are examples of the former. Most of these plants have widely spreading roots which are just beneath the surface.

The development of peat in swamps checks the drainage of an already poorly drained surface and also hinders evaporation. The level of the

[97] MacDonald, D. F., Some factors of Central American geology that may have a bearing on the origin of petroleum, Bull. Am. Assoc. Pet. Geol., vol. 4, 1920, pp. 263–268.

[98] Davis, C. A., op. cit., pp. 626–627.

[99] Vaughan, T. W., The geologic work of mangroves in southern Florida, Smithsonian Misc. Coll., no. 1877, vol. 52, 1909, pp. 461–466.

water rises, and the swamp expands laterally. This lateral expansion may result in the entire surface becoming swampy. Ultimately a "high moor" results, with the water surface of low domal shape. After a prolonged rainy period, this condition of instability may result in a "bog burst" and parts of the adjacent regions may become deluged with foul-smelling black mud. A bog burst inland from the town of Stanley on the Shetland Islands produced a stream of black mud over 100 yards wide and 4 to 5 feet deep which flowed through the town into the harbor, blocking the streets, wrecking one or two houses, completely surrounding others, and smothering a child and perhaps an old man.[100]

Extensive swamps not uncommonly have pools of water over the central portions which are so toxic that life cannot exist in them. Streams flowing into swamps may have the swamp vegetation "climbing" the stream channel to its source. Swamps on deltas and flood plains usually have considerable inorganic matter incorporated with the organic, and this may constitute the major portion of the deposits. In swamps not connected with streams the inorganic matter is limited to that derived from plants, carried in solution or in the colloidal state into the swamp waters, and that contributed by the atmosphere.

Most swamp accumulations of the present time exist under physiographic conditions which preclude preservation, as no possibility of burial exists. Such is the case for the vast accumulations of organic matter in many swamps over the Laurentian shield. It is very probable that accumulations under similar conditions obtained on some parts of the earth's surface during every period of earth history since the appearance of land vegetation. Extensive plains undergoing slow submergence, and large delta plains being built into shallow seas with rising sea level, present the conditions making possible the burial of organic accumulations. Tremendous thicknesses then become possible.

Hydrogen sulphide commonly is not apparent in fresh-water swamps. This is thought to be due to the scarcity of sulphates in solution in the fresh waters.

Swamps Connected with Basins. Basin swamps exist about the margins of small or shallow lakes having little wave activity, and marginal to protected bays of larger lakes. The lakes may be of any origin. The swamp accumulations may fill the bays and lakes so as to bring them to extinction.

Such plants as *Chara* grow in relatively deep water, and other plants in zonal arrangement fill up the entire space to dry ground. Each zone is characterized by some dominant group of plants whose arrangement in northern United States from deepest water shoreward is as follows:

[100] Barkley, A., Abstract, in Proc. Geol. Soc. London, 1887, p. 9.

> (1) the pond weeds, Potamogeton; (2) the white and yellow pond lilies, Castalia and Nymphæa; (3) the lake bulrushes, Scirpus; (4) the amphibious sedges, Carex, Eleocharis, etc., especially the turf-forming slender sedge, *Carex filiformis L.*, or species of similar habit.[101]

In other latitudes there may be plants of different relationships, but similar habitat. Thus, on the Texas coastal plain area the arrow leaf is a common shallow-water plant.

The various plants form floating mats which catch sediments and afford support for grasses and other plants, and ultimately a mat may cover an entire lake. At first this mat rises and falls with the lake. It is then a quaking bog. New plants invade the mat, and finally it may support large trees. The result is the complete filling of the basin with a sponge-like mass of semi-decayed organic matter.

The swamp deposits of flood plain and delta basins are likely to differ in several important respects from the characteristics given. These swamps usually receive their waters from flooded streams, and at the same time they receive mud. They usually contain much black mud of which the inorganic constituents may compose the greater portion. Deposits of pure peat are exceptional, particularly in the swamps of rivers with narrow flood plains. The basins on wide flood plains densely covered with vegetation may become filled with good peat if the basins are sufficiently far from the streams for the vegetation to filter the water before the basins are reached. River swamps acquire fish from each flood, and their remains may become buried in the deposits. The swamps may dry out for parts of each year, and the deposits thus become more or less mud cracked and oxidized.

Swamps on Flat or Gently Sloping Surfaces. Swamps of this type are determined by the climatic conditions of high relative humidity, regular and relatively high precipitation, and low evaporation. They are most common in middle latitudes on both sides of the equator.

The plants inhabiting swamps of this class are of varied types and of different kinds in different stages of swamp development. In the latitude of the United States, mosses, ferns, canes, sedges, grasses, rushes, alders, cedars, spruces, tamaracks, etc. are common flat-area swamp plants. In Canada, mosses, ferns, and scouring rushes are important plants in this type of swamp. The tundra is the subpolar expression of the flat-area swamp.

Swamp Deposits

Swamp deposits consist of peat, iron oxides and carbonates, muds, sands, and occasional marls. The peat is usually entirely autochthonic. The iron

[101] Davis, C. A., Origin and formation of peat, Bull. 38, U. S. Bur. Mines, 1913, p. 172.

oxides are almost always porous and cavernous, but in some cases they are slag-like and hard and in others loose and earthy. The Fe_2O_3 content ranges from about 20 to 60 per cent. Silica is always present to a maximum of about 15 per cent. The phosphoric acid content is generally high, some deposits containing as much as 10 per cent.[102] The iron carbonate of swamps is usually in small quantity. Bog iron "ores" rarely attain a thickness of more than 3 to 4 feet and generally are without stratification. They are relatively resistant to erosion, and patches not uncommonly occur on the tops of residuals, and beneath flat lands they constitute one type of "hard pan." The shales of swamps may or may not be laminated. They are usually highly carbonaceous, and very commonly in paralic swamps they carry pyrite and marcasite as nodules, thin films, and replacements of shells. Sands are not common in swamps. The marls of swamps usually lie beneath the plant accumulations.

THE LACUSTRINE ENVIRONMENT AND ITS SEDIMENTS

From the point of view of the sediments, lakes may be classified as glacial river, seashore, and lakes formed by crustal movement. Each of these may not materially differ from the others in the general character of its deposits, but the manner of genesis determines relationships to other deposits. Lakes may also be considered from the points of view of freshness or salinity of waters. There are also differences dependent upon climate.

Fresh-water Lakes

Distilled water has its greatest density at 4°C., and this figure may be considered applicable to the waters of non-saline lakes. Cooling of non-saline water, hence, increases density to the maximum at about 4°C., following which the water expands to the freezing point. Deep lakes of temperate regions whose surface waters during some part of each year are chilled to the condition of greatest density have the surface waters sinking to the bottom, thereby displacing warmer waters which are brought to the top to become chilled in turn, thus producing a complete overturn of the lake waters. Further cooling at the top decreases the density until the water changes to ice. The ice protects the waters beneath, and these gradually rise in temperature. The spring melting of the ice finds the bottom waters warmer and lighter than the condition of maximum density, and thus the surface waters sink to the bottom and a second overturn takes place. The two overturns bring to the bottom waters plentifully supplied with oxygen, and this is utilized by bottom organisms and assists in de-

[102] Beck, R., The nature of ore deposits, Transl. by Weed, W. H., 1909, p. 99.

composition of organic matter on the bottom or in the bottom waters. In course of time the oxygen is removed and its place taken by carbon dioxide. During the times of overturn the lake waters have approximate density throughout, and circulation of course extends to the bottom. At other times circulation is largely confined to the upper waters.

The waters of tropical lakes do not overturn, with the consequence that the bottom waters remain low in oxygen and high in carbon dioxide. The heavier and colder waters are always on the bottom.

The lakes of polar regions likewise tend to have the heavier waters on the bottom, but these waters are warmer than those of the surface, as the latter are nearer the freezing point. Here, likewise, there is no overturn. It must not be assumed that there are sharp boundaries between the lakes of the different parts of the earth, as a lake may be of tropical character one year and temperate character the next.

Thus, fresh-water lakes fall into three general classes: (1) Tropical, colder waters at the bottom, warmer at the top, no overturn, direct stratification; (2) polar, colder waters at the top, warmer at the bottom, range 0 to 4°C., no overturn, indirect stratification; (3) temperate, warmer waters on top and colder waters on bottom in summer, and colder waters at top and warmer waters at bottom in winter, summer stratification direct, winter stratification indirect, two overturns annually.

The waters of lakes are thus more or less thermally stratified. There is an upper stratum, known as the *epilimnion*, whose temperature is much the same throughout, as it is stirred by convection and wind currents. The epilimnion contains an abundance of oxygen due to its broad contact with the air and to production by plants through release of oxygen from carbon dioxide. At the bottom is a stratum known as the *hypolimnion*, whose waters are relatively stagnant, generally low in oxygen and high in carbon dioxide, generally colder, and have a more uniform temperature and a higher hydrogen ion concentration (low pH) than the epilimnion. The intermediate stratum is known as the *thermocline*, or stratum of rapid decrease of temperature with depth, whose limits are somewhat arbitrarily fixed as those of the region in which decrease of temperature with depth equals or exceeds one degree per meter.[103] The thermocline is fairly sharply defined from the epilimnion, and it grades off into the hypolimnion.

The fact of thermal stratification has important bearings on the sedimentation and biology of lakes. Each stratum of a lake has its individual biological characteristics, with the total environment of that stratum giving

[103] Birge, E. A., and Juday, C., Bull. Bureau Fisheries, vol. 32, 1912, p. 547; Kindle, E. M., The rôle of thermal stratification in lacustrine sedimentation, Trans. Roy. Soc. Canada, vol. 21, 1927, pp. 1–35.

rise to its own peculiar sedimentary products. The epilimnion with its favorable summer temperature, abundance of oxygen, sufficiency of carbon dioxide, and favorable light relations will be the place of the greatest abundance of life. The conditions are those of oxidation. The heavy waters in the hypolimnion and the higher viscosity as a consequence of coldness favor wide distribution and excellent sorting of those fine sediments which remain for a considerable time in the upper waters of a lake. The high carbon dioxide content of the lower waters and the low pH content favor solution of settling and bottom carbonate matter, thus not favoring the formation of lime carbonate deposits in the hypolimnion and essentially limiting these to the epilimnion and the thermocline. The conditions in the hypolimnion favor reduction of inorganic matter.[104]

The hypolimnion of polar lakes is apt to have less organic matter passing through it, and there is generally less growth on the bottom with less use of oxygen; hence, these waters may not have a scarcity of oxygen and an abundance of carbon dioxide.

Transportation of mechanical sediments in fresh-water lakes varies with the type of lake, the size, the circulation, and the character of the water. In the lakes of temperate and warmer regions muddy waters, because of density, may settle beneath the surface to mingle with the cold and heavy waters beneath the thermocline, and the muddy waters may go to the bottom.[104] In Lake Geneva the water from the Rhone River flows as a strong current directly to the deep part of the basin, and the same is true of the Rhine where it flows into the Bodensee (Lake Constance). The mingling of the river and lake waters on the sides of the current of the former lowers the density of the cold waters, and sediments are likely to be precipitated, and structures of the nature of subaqueous dikes may be built. Warm stream waters relatively free from sediments are lighter than those beneath the thermocline and thus mingle with the waters of the epilimnion, and there is a tendency for any sediments in such stream waters to be deposited over wide areas of a lake. However, the lesser density and lesser viscosity somewhat lessen such distribution. Stream waters sinking beneath the thermocline tend to deposit their sediments in the deeper parts of the lake basin, and consequently there is a lessened areal distribution.

Glacial lakes or the lakes receiving the cold melt waters of glaciers differ

[104] Heim, A., Der Schlammabsatz am Grunde des Vierwaldstättersees, Vierteljahrschrift d. Naturf. Gesell. in Zurich, vol. 45, 1900, pp. 164–182; Forel, F. A., Handbuch der Seekunde, Bibliothek geogr. Handbücher, 1901, p. 34; Halbfass, W., Grundzüge einer vergleichenden Seekunde, Berlin, 1923, pp. 80–81. The work by Halbfass is a monograph on lakes in which their distribution, origin, morphology, hydraulics, the optical properties of their waters, etc. are considered in detail, but little is said about the life of lakes or their sediments.

in their inflow from lakes receiving their waters from streams, springs, and rains. In the first place, the melt waters may be just about the freezing point and hence on the low-temperature side of the conditions of greatest density, so that as the temperature rises they tend to sink, and thus these lakes may have indirect stratification; and secondly, many glacial lakes may have much of the inflow entering near the bottom, whence it rises toward the top, as shown in figure 117, thus giving to these lakes a circulation differing somewhat from that of those lakes into which the inflow enters in large part near the top. If the melt waters are lighter than the bottom waters and do not contain too great a burden of sediments, the transportation may largely be confined to the upper waters of the lake no matter where the melt waters enter. The high density and viscosity of the cold waters retard settling, and the various currents spread the melt waters; and thus fine

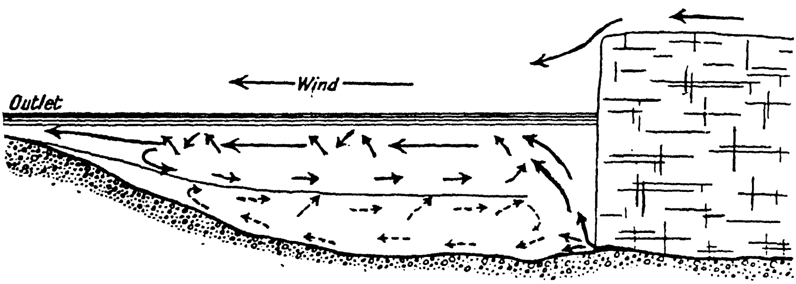


FIG. 117. CIRCULATION OF WATER IN A GLACIAL LAKE
The water is shown entering from beneath the bottom of the glacier and the wind blowing from the glacier over the lake. The assumed direction and strength of the water currents are indicated by the arrows. After Antevs, E., Mem. 146, Geol. Surv. Canada, 1925, p. 41.

material in suspension may become diffused throughout the lake waters and attain deposition over the entire basin. According to Antevs, "This is evident from the spreading of fine glacial mud over the entire area of large lakes and its deposition far away from the ice edge where the water was shallow as well as where it was deep."[105] Transportation seems to be brought about in the upper waters of glacial lakes by winds of an anticyclonic type which set the water in motion away from the ice, and through currents developed by the great volume of melt water during times of warmth. The transportation and deposition in a glacial lake would be governed by the agitation of the surface water, the temperature of the bottom, the temperature of the melt waters, the shape of the lake basin and thus the currents

[105] Antevs. E., Retreat of the last ice sheet in eastern Canada, Mem. 146, Geol. Surv. Canada, 1925, p. 25.

to the outlet, the physical and chemical properties of the lake and melt waters, and the characters of the transported sediments.

Lakes of tropical regions have their warmest and lightest waters always at the top and the heaviest and coldest adjacent to the bottom. There is no overturn and hence little circulation in the deeper waters, which are likely to become foul with partially decayed organic matter. Stream waters with a heavy burden of sediments may sink beneath the surface waters and thus carry sediments and oxygen to the bottom. The deeper waters of tropical lakes are likely to be copiously supplied with carbon dioxide, thus rendering unlikely the deposition of calcium carbonate in waters of any depth.

The sediments deposited in glacial lakes may or may not be varved, depending on the continuity and character of deposition. The sediments of temperate, tropical, and polar lakes not connected with glaciers may not even be stratified except in a large way, as deposition may be essentially continuous, and in the temperate lakes and the shallow waters of tropical lakes the sediments tend to be rather thoroughly worked over by organisms.

Salt Lakes

Waters flowing into salt lakes are usually lighter than the waters into which they flow, and thus the fresh waters tend to flow on top. Rapid deposition of suspended sediments and colloids takes place on the mingling of the two waters. If the salinity of the waters of the lake is high, the bottoms will have limited life, and thus working over of bottom materials will be negligible. Good stratification is likely.

Lake Processes

These are mechanical, chemical, and organic. The mechanical processes differ from those of the sea in the absence of tides and the possibility, in the fresh-water lakes, of small particles remaining indefinitely in suspension.

The inorganic chemical processes of lakes do not appear to be of great moment except in lakes of arid regions, where evaporation and processes initiated by concentration play an important rôle in the precipitation of saline residues and the flocculation of colloids.

Organic processes, on the other hand, play a considerable rôle. Lakes are inhabited both by animals and by plants. Gastropods and pelecypods are the most abundant animals and crustaceans are common. The shells usually are fragile and break up soon after the deaths of the builders. The plant life of lakes is of great importance. The margins of many small lakes are inhabited by many species, and much of the water coming to such lakes must filter through a sponge of living and dead vegetation, with the result

that very little detrital matter may reach the bottoms, nearly the whole of the deposits being organic. The algæ and green plants of lakes precipitate large quantities of calcium carbonate.

Lakes have no true littoral deposits, but fluctuations of level may produce a shore zone which in some respects partakes of the characteristics of the ocean littoral. This fact may be expressed in the sediments in the mixing of the characteristics of two realms of deposition,—mud cracks, rain prints, and the tracks of land animals associated with shore bedding and the fossils of lacustrine animals. About shallow lakes with small wave activity the shore is not eroded, and it and the adjacent shallow bottom become overgrown with vegetation. The deposits of lakes with strong wave action grade outward from the sands and gravels of the shore to extremely fine muds in the center, and a typical deposit of a lake with strong wave action should consist of an encircling belt of shore gravels, an inner concentric belt of sands within which is a belt of sandy marly mud, and in the center fine muds or marls essentially free from grit, each belt grading gradually into those adjacent. As fresh water permits slow settling of the fine sediments, these remain in suspension a long time. Some are ultimately carried to the middle of the lake and deposited in thin laminations, each beginning with the coarsest material carried and grading upward into the finest in contrast to the deposits of marine deltas, where, because of flocculation, the coarsest materials may be found in the upper portion of a lamination.[106] As deposition of the central portion of a large lake may be essentially continuous, lamination may not develop, and there may be absence of sharp boundaries between beds. Such sharp boundaries are believed originally to form in most marine sediments because of the rapid precipitation which occurs in salt water.[107] Organisms may subsequently work over the fine deposits of lakes, with consequent destruction of any features of deposition.

The absence of significant tides in lakes decreases development of shore or littoral currents. This hinders the formation of asymmetrical ripple mark. Since there is nothing limiting the development of wave ripples, these may assume relatively greater importance in lakes than in the sea.

Since lakes generally are of limited area, their deposits are similarly so. These commonly have rudely spherical or elliptical outlines in horizontal plan, but they may be greatly elongated or horseshoe-shaped, as is commonly the case for river lakes.

The animals of fresh-water lakes are characteristic. Brachiopods, echinoderms, corals, and cephalopods never appear to have lived in fresh-water

[106] Kindle, E. M., Diagnostic characteristics of marine clastics, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 907–909.

[107] Kindle, E. M., op. cit.

lakes, but strangely enough, medusæ occur in Lake Tanganyika and a few other places. Gastropods and pelecypods seem to have been inhabitants of lakes since the earliest geologic records of lake deposits; in fact, their shells are so abundant in some lakes as to give rise to considerable thicknesses of shell marl. Microscopic organisms, both animal and plant, are abundant in lakes and contribute to marl deposits, but they have rarely been identified in the deposits of ancient lakes. Fish are common in most lakes, but they have little value as criteria of environment, as many, like the salmon, periodically go from salt to fresh water, and others, as the eel, from fresh to salt water. Fish also appear to become easily adapted, as exemplified by the sharks of lakes Titicaca and Nicaragua. Seals also show the same adaptations. Kindle's studies of Lake Ontario indicate that in this lake "the great bulk of the species live within 25 feet of the surface" and that the "maximum depths appear to be tenanted chiefly if not exclusively by small hair or flesh colored worms."[108] It is not known whether or not this applies to other large lakes.

Most small lakes have an abundant growth of plants about their borders, and the shallow waters are aggressively invaded by a large number of species. Conspicuous in this respect are such plants as the water lily, arrow leaf, cattail, pickerel weed, and sphagnum. Small shallow lakes ultimately are brought to extinction through plant growth, and in this way their deposits pass vertically and laterally into those of swamps. The higher green plants in Lake Ontario extend down to depths of 15 feet. An algal and diatom flora extends to depths of 150 feet or more, and below 200 feet there seems to be no plant life.[109] Remains of terrestrial animals and plants may occur in the deposits of any lake.

In addition to the general characteristics given, there are others which are connected with, or arise from, the method of origin.

Glacial lakes receive glacial or glacio-lacustrine deposits in the early stages of their history, and the deposits rest upon, grade laterally into, and more or less dovetail with deposits of glacial origin and not uncommonly of glacial deposition. Lakes of this origin usually are small, contain fresh water, and exist under climatic conditions favoring the growth of such plants as sphagnum. Their deposits ultimately pass upward into some phase of peat material.

River lakes are shallow, usually elongated, and surrounded and underlain and overlain by deposits of the piedmont, valley-flat, or delta environment. They usually contain fresh water. The faunas of river lakes are as a rule

[108] Kindle, E. M., The bottom deposits of Lake Ontario, Trans. Roy. Soc. Canada, vol. 19, 1925, pp. 17–72.

[109] Kindle, E. M., op. cit.

derived from the waters which produced the lakes, and they may receive a new supply at each flood. River lakes may be much reduced during dry seasons, and wide areas about their margins may become extensively mud cracked and marked with rain prints and the tracks of animals. At each flood time they may receive a deposit of river mud. These deposits, with additions from animals and plants, bring them to extinction. The deposits are essentially mud, commonly well laminated, although this feature may be destroyed by mud cracking. The deposits of river lakes may contain an abundance of fish remains.

Seashore lakes develop where portions of the sea are cut off through the formation of a bar or barrier. They may contain either fresh or salt water. Lakes of this origin usually are shallow and generally have streams emptying into them on their landward sides. The deposits of these streams, together with material brought over the barrier by winds and occasional high waves, may bring the lakes to extinction or change them into marine swamps. The deposits of seashore lakes usually rest on shallow-water marine sediments, which by gradual transitions through brackish-water deposits may grade into those of fresh water. The fresh-water deposits may contain marine shells because of the occasional entrance of salt waters in storms and the occasional shells carried in by birds and other flying animals. The gradual change from salt water to fresh may lead to some animals becoming adapted to the fresh-water habitat. Difficulty of interpretation is obvious.

Lakes formed by crustal movement include the largest now in existence, and doubtless such has always been the case. They may be either fresh or salt. Lakes Nicaragua and Titicaca, the Great Lakes, and the Caspian are examples. Not uncommonly these lakes contain animals of marine ancestry, as exemplified by the seals of the Caspian Sea, the sharks of Lake Nicaragua, and the medusæ of Lake Tanganyika. The physical character of the shore deposits of large lakes differs little from those of the sea. As the centers are far from shore, there is plenty of opportunity for the elimination of the coarser materials before the centers are reached, with the consequence that the deposits there are of an extreme degree of fineness. The deposits of Lake Ontario probably are fairly illustrative of those of large lakes. The sediments of the deep-water area of depths ranging from 200 to 700 feet consist of very fine mud of jelly-like consistency. This contains no molluscan life, and shrimps, minute worms, and diatoms represent its fauna and flora (the bacterial flora is not considered). The deep-water sediments are surrounded by a belt of coarser sediments consisting of sandy mud, sand, and gravel. This belt has a molluscan fauna. Parts of this bottom consist of bed rock on which there are no sediments.[110]

[110] Kindle, E. M., op. cit.

Salt-water lakes seem to be characterized by a greater production of hydrogen sulphide than those of fresh water, and this may become so abundant in salt-water bodies as to render their bottoms and lower waters unfit for habitation by organisms.

The Lake Cycle

From the time of origin most lakes begin to disappear. They are filled up by deposition of sediments and cutting down of outlets (seashore lakes excepted). The latter event causes the waters to recede, and the shore deposits migrate downward and centralward, ultimately covering those of the deeper waters. The top deposits may thus be coarser than those immediately below,[111] but if a lake passes into a swamp the final deposits are composed of peat.

Lake Deposits

Lake deposits consist of marl, tufa, sands, gravels, peat, iron oxides, iron carbonate, silicon dioxide, salt, gypsum, and other evaporation products.

Lake marl is composed of calcium carbonate mixed with a variable proportion of impurities. The colors range from white to gray and red, depending on accessory substances and the degree of oxidation of iron which may be present. It is composed of a mixture of coarser and very much finer matter, the proportion of the former ranging from 50 to 95 per cent and both the finer and the coarser parts consisting very largely of incrustations formed on green plants. Many varieties of plants may participate in its formation. Davis[112] assigned the chief rôle to *Chara*, but there appear to be few good reasons for this assignment, and shells in some cases are important in forming marl deposits. All marls contain more or less carbonaceous matter. According to Kindle, marl accumulation takes place largely in the epilimnion under conditions where the "thermal stratification is protected from the mixing effect of high wind and waves."[113]

Deposits of marl are extensive in some lakes, particularly those smaller ones whose shores are protected by vegetation against the entrance of mud and sand or by barriers against wave and current action. A lake near English Bay, Anticosti Island, has an area of about 100 acres over which marl is known to have a maximum thickness of at least 12 feet. These marls appear to be largely composed of the shells of three species of gastropods. There are several other lakes on Anticosti more or less filled with marl.

[111] Mansfield, G. R., The origin and structure of the Roxbury conglomerate, Bull. Mus. Comp. Zool., vol. 49, 1906, p. 120.
[112] Davis, C. A., The natural history of marl, Jour. Geol., vol. 9, 1901, pp. 490–506.
[113] Kindle, E. M., op. cit., 1927, pp. 1–35.

Tufa has been stated to result largely from the evaporation of highly concentrated waters, but it seems certain that algæ may be of major importance in its deposition. Its most significant occurrences are largely in regions which at the times of deposition seem to have been arid or semi-arid, as in former Lake Lahontan of the Great Basin region.[114]

Lake clays and silts are very similar to those of marine origin. However, they of course contain fresh-water shells, and the great length of time that matter remains in suspension tends to make deposition fairly continuous, to eliminate sharp contacts, and to bring extremely fine grained muds to the centers of lakes. Considerable carbonaceous matter is present in lake clays, on the basis of which it has been suggested that lake deposits might be differentiated from marine.[115] The dry weight of vegetable matter annually formed in Lake Mendota at Madison, Wisconsin, totals 2,203,000 kgm., an average of about 800 kgm. per acre,[116] of which 1,112,000 kgm. are derived from *Potamogeton* and 736,000 kgm. from *Vallisneria*. Considerable parts of this vegetable material are deposited with the clays; some of it is preserved, but much is dissipated by bacteria and other organisms after deposition.

The sands and gravels of lakes are not particularly different from those of marine origin. The thicknesses are small.

Concentration or evaporation products are extensive in the lakes of some dry regions. These have been considered in connection with the products of sedimentation.

Peat has been considered in connection with carbonaceous sediments.

Iron oxides and carbonates are deposited in some lakes and reach considerable extents. Some lakes of Sweden,[117] Finland, European Russia, Canada, Maine, and probably elsewhere have deposits of limonite forming in them at the present time. In the Swedish lakes the limonite is deposited about 10 meters from the shore and reaches a maximum thickness of about one-half meter. The deposits occur in the form of elliptical and irregular patches which are in the quiet places where there is an abundant growth of vegetable matter. The iron oxide settles to the bottom as mud of blackish, brownish, and greenish colors. It is filled with plant débris, both of algal and higher plants, and is rich in gelatinous silica. In hardening, the mud forms "either compact lumps (rusor), small disks or balls," or concre-

[114] Russell, I. C., Geologic history of Lake Lahontan, Mon. 11, U. S. Geol. Surv., 1885.

[115] Matthew, G. F., On a method of distinguishing lacustrine from marine deposits, Proc. Roy. Soc. Canada, vol. 4, 1883, pp. 147–149.

[116] Rickett, H. W., A quantitative study of the larger aquatic plants of Lake Mendota, Trans. Wisconsin Acad. Sci., vol. 20, 1921, pp. 501–527, particularly table 7, p. 521. The smaller aquatic plants are not included in these figures.

[117] Beck, R., The nature of ore deposits, Transl. by Weed, W. H., 1909, p. 100.

tionary masses about animal and plant remains. The deposits commonly contain phosphorus as earthy vivianite; and a considerable quantity of manganese, probably in the form of wad, is also very generally present.

Iron carbonate occurs in the deposits of lakes which are rich in organic matter. Due to the readiness of oxidation, the quantity is usually limited. Sulphide of iron is present in the same relation.

The silicon dioxide brought to fresh-water lakes probably remains indefinitely in the water. In salt-water lakes it is flocculated and precipitated as in marine waters. Chert and flint thus result in the deposits of some lakes.

THE CAVE (SPELEAN) ENVIRONMENT AND ITS SEDIMENTS

Although caves in some regions have extensive ramifications, the deposits made in them are small. The important cave regions of the United States are the Mississippian limestone areas of southwestern Indiana, southern Illinois, and west-central Kentucky and the continuation around the southern end of the Cincinnati arch into eastern Kentucky and Tennessee; the limestone areas of the Ozarks; and the Cambro-Ordovician areas of the southern Appalachians. A great cave region of Europe is that of Karst on the eastern shores of the Adriatic. From the quantitative point of view, the cave environment is the least important for deposition of sediments.

The darkness of caves limits their abundance and variety of life. Many forms which make caves their permanent homes are eyeless, or have non-functional eyes. Other animals make caves places of refuge, but spend the major portion of their lives in the open. Some nocturnal forms, as bats, live in caves during the daytime. There is thus the possibility of a considerable range in variety of organic remains in caves.

Water-worn caves are wet, and as they largely develop through solution of rock, insoluble parts remain for shorter or longer periods of time attached to the roofs and walls. During times of heavy rainfall the smaller caves may be full of water, and the water may contain considerable quantities of suspended sediments. Some of these may be deposited, but the tendency is to remove rather than to deposit. Wind-worn caves ordinarily are without deposits so long as the conditions of formation obtain.

Sediments Deposited in Caves

The sediments in caves are deposited by the streams flowing therein, by the ocean or other waters in cases of submerged caves, by material falling from the roofs, by evaporation and chemical reactions of the waters which enter caves, by bacterial precipitation, by the ground waters which fill caves when they are brought below ground-water level, and by organisms.

The mechanical sediments deposited by streams are small in quantity and local in distribution. The material falling from the roof may be sufficiently great to cover the floor locally to depths of several feet. Caves of lands undergoing submergence become filled with deposits of the submerging waters. These may be either of mechanical or chemical origin and may be in layers parallel to the cave floors and approximating the horizontal.

Materials deposited in caves by evaporation or chemical action form the stalactites, stalagmites, and kindred substances. Calcium carbonate is the common composing material of stalagmites and stalactites, but some are composed of silica, iron oxide, and rarer substances as sphalerite, galena, etc. It is not recorded that bacterial precipitation takes place in caves, but as it has been reported in mines, there are no reasons why it should not also occur in caves.[118] The rates of growth of stalactites have been determined in a few instances.[119] Stalactites formed in the inspection tunnel of the Wilson Dam, Muscle Shoals, Alabama, the dam having been put in operation early in 1925, were measured early in 1930. They ranged in length between 12.7 and 22.8 cm., and the longest observed was 38.7 cm. The average diameter was 0.5 cm. near the top, and at the bases the diameters ranged between 1.2 and 3.8 cm. This gives an annual rate of growth ranging from 2.5 to 5 cm. A tubular stalactite 8.9 cm. long, 1.3 cm. in diameter at the base, and 0.6 cm. in diameter at the tip grew in the arch of a concrete culvert in Washington, D. C., in two years. A copper sulphate stalactite 67.5 cm. long and 2.5 cm. in average diameter formed in the 1400-foot level of the Briggs Copper Mine at Bisbee, Arizona, in seventeen months, a rate of growth averaging 3.95 cm. per month.[120] Allison[121] described stalactites forming in a coal mine and increasing in length at a rate of 0.1 to 1.44 cm. a month, and Curtis[122] states that aragonite aggregates grew in drops of water at the rate of about 0.9 cm. in three months. As the rates are dependent upon a considerable number of variable factors, it is doubtful if any generalization as to rates of growth can be made and be of much value, although Allison has presented methods by which the age of stalagmites and stalactites may be determined.

Caves which pass beneath the level of the ground-water table may be-

[118] Parry, J., Minerals deposited by bacteria in mine water, Chem. News, vol. 125, 1922, pp. 225–228, 241–243, 257–259.

[119] Johnson, W. D., Jr., The rate of growth of stalactites, Science, vol. 72, 1930, pp. 298–299.

[120] Mitchell, G. J., Rate of formation of copper sulfate stalactites, Trans. Am. Inst. Min. Eng., vol. 66, 1921, p. 64.

[121] Allison, V. C., The growth of stalagmites and stalactites, Jour. Geol., vol. 31, 1923, pp. 106–125.

[122] Curtis, J. S., Silver-lead deposits of Eureka, Nevada, Mon. 7, U. S. Geol. Surv., 1884, pp. 56–58.

come completely filled with minerals deposited from solution, and some of the onyx deposits are thought to have originated in this way.[123] The solution cavities which are said to occur in the Tamasopa limestone of Mexico are now beneath ground-water level, and it is not unlikely that some of them are receiving deposits from solution.

The organic deposits in caves consist of bones and excrements of cave-dwelling animals and the bones of the animals upon which they preyed. The Pleistocene caves of Europe, and southern France in particular, were inhabited by man, whose bones, implements, and the bones of the animals upon which he fed now occur in the deposits covering the floors. The guano of caves is usually referred to the excrements of bats. The distribution is irregular and the quantity is small.

Cave Deposits in the Geologic Column

Not many are known. The Mississippian and older limestones of Missouri and adjacent states contained caves prior to the deposition of the Pennsylvanian and younger sediments, and some of the caves became filled by these subsequent deposits. Some of the ore bodies of the lead and zinc district of Missouri, Kansas, and Oklahoma appear to have been deposited in caves.[124] Many of the Pleistocene caves are noted for their deposits of organic material.

Mixed Continental and Marine Environments

Mixed continental and marine environments are made where the ocean and the continents and smaller land masses meet. This contact may be placed in the four classes of littoral, delta, estuary, and marginal lagoon. Marine processes are dominant in the littoral; in the delta there is a strong contest between the sea and the land, the delta attesting the dominancy of the land processes; the estuary in some parts of its area changes to fresh or brackish water at each low tide and to brackish or salt water at each high tide; and the marginal lagoon ranges from fresh to salt water, and in some regions to highly saline waters. The sediments of the littoral are derived from both the land and the sea, but for the most part they are deposited by oceanic waters; those of the delta are mostly derived from the land and deposited by fresh waters; and both the land and the sea may make more or less equal contributions to the deposits of the estuary and the marginal lagoon.

[123] Merrill, G. P., The onyx marbles, Rept. U. S. Nat. Mus., 1895, pp. 541–585.

[124] Siebenthal, C. E., Origin of the zinc and lead deposits of the Joplin region, Bull. 606, U. S. Geol. Surv., 1915, pp. 159–161.

THE LITTORAL ENVIRONMENT AND ITS SEDIMENTS

The littoral environment is defined as that portion of the sea bottom which is exposed at low tide. During ordinary tides this has somewhat constant lower and upper limits; during the neap and spring tides the limits are both higher and lower than at other times. Exposure and submergence may also arise from storms and earthquake waves. These are irregular and may be of greater extent than are those due to tides.

Extent of the Littoral Environment

At the present time the ordinary width of the littoral zone is small. There are places, as in the Bay of Fundy, where the great rise of the tides gives to the zone a width of a mile or more. Such places, however, are few. It seems probable that during those times of earth history when the lands were near base level, high tide may have submerged many square miles which were exposed at low tide, and it is possible that the width of the littoral may have been a dozen or more miles. The west shores of Hudson Bay perhaps more nearly illustrate such conditions at the present time. Throughout long stretches of the coast between Port Churchill and Chesterfield Inlet there are extensive areas which are covered by water at high tide and exposed at low tide, the difference in water level being about 12 feet, and the widths of the tidal flats range from a few hundred feet to 6 or 8 miles, a couple of thousand or more square miles thus being alternately exposed and covered each day. The flats are particularly well developed for some 50 miles northwest of latitude 60° N., where at low tide the waters of Hudson Bay may not be visible from the shore of high tide level.[125] The Wattenmeer of the North Sea similarly is an extensive tidal flat.[126] It seems probable that some of the epicontinental seas of the Paleozoic, as for instance those covering the upper Mississippi Valley during the Cambrian and Ordovician, may have had conditions somewhat like those of Hudson Bay.

The present area of the littoral environment has been estimated at 62,500 square miles.[127]

Conditions in the Littoral Environment

The most important facts connected with the littoral environment are the exposure twice each day and the more or less constant wave activity.

[125] Lund, R. J., Personal communication.

[126] See papers by Richter, R., Senckenbergiana, 1920, and Krümmel, O., Über Erosion durch Gezeitenströme, Petermann's Mitth., vol. 35, 1889, pp. 129–138; Über die Umformung der Küsten durch die Meeresströmungen, Mitth. Geogr. Gesell. Hamburg, 1889–90, p. 221.

[127] Murray, J., and Renard, A. F., Challenger Rept., Deep sea deposits, 1891, p. 248.

Each condition makes it difficult for organisms to establish permanent homes, with the result that few species have become adapted. Some are attached forms, as certain algæ and such invertebrates as *Mytilus* and *Balanus*. *Mya* burrows in the mud and there are others which tide over the periods of exposure by crawling under rocks or have means for closing their shells. There are, however, many individuals of such species as have become adapted.

The strong wave action which frequently prevails in this environment produces great wear on everything that enters. Rock particles are rounded; shells are ground to powder; logs are polished smooth; etc.

The shore environment is not the same everywhere. Some portions consist of gently sloping bare rock surfaces; other portions are more or less vertical wave-cut cliffs; some shores are composed of gravels, others of boulders, and still others of sand, mud, and shell matter. Some shores are none of these things, but from low to high tide level the entire sea bottom and the land surface inland are covered with a dense growth of vegetation consisting of algæ, grasses, sedges, reeds, etc.; the algæ live in the salt and brackish waters and the other plants in the fresh waters inland from the sea, a part of this inland surface being below high tide level, but bathed by fresh waters because of large contributions of such from the land and because this fresh water and the vegetation serve as a dam to hold the salt water out. A small-scale illustration of this nature may be seen on the Gulf of St. Lawrence between the mouth of the Mingan River and Eskimo Point. One type of the littoral environment is where mangroves are advancing into the sea. A particular facies is the coral reef. A littoral bordered by extremely shallow waters into which numerous streams are flowing may be bathed by waters which are fresh most of the time. Such seem to be rare at the present time, as most of the littorals are bordered by fairly deep waters, but may have been frequent in some of the shallow epicontinental seas of the Paleozoic.

A bare rock shore receives no littoral deposits. The mud and muddy sand shore is inhabited by many mud- and sand-eating organisms which live within the sediments and leave their shells therein on death. The solid rock shore may be covered with cemented forms or those attached by byssal threads. The shores of sand, gravel, and boulders usually are without macroscopic organisms, other than vagrant benthos.

Sedimentary Processes in the Littoral Environment

The sedimentary processes of the littoral environment are mainly mechanical. The sediments in considerable if not largest part are derived from the shore through rock breaking and grinding, aided by frost action and

undermining. Organic matter is limited, although on some coasts the sediments are mainly organic. There is some work done by the wind, but it is indeterminate and probably small, but wind deposits of beach derivation may occur inland from the shore. The exposure to the atmosphere twice each day permits some evaporation, and mud cracks may develop during the exposures. The exposure also may assist in the cementation of some of the sediments.[128]

Characteristics, Thicknesses, and Associations of Littoral Sediments

The deposits made in the littoral environment are in large part the result of wave deposition. There is much variety, and the sediments range from boulders, gravels, sands, and muds to organic matter composed of shells, logs, and seaweeds. Some shores are composed of sands for long distances. In such cases the land adjacent to the shore usually is not high, and the shore is regular and uniform, thus permitting uniformity of wave action. The average shore is irregular, with a variety of relief to the adjacent land. The consequence is that the shore deposits show extremely great irregularity. Lenses of mud may be found lying in the midst of sand, gravel, or boulders. A walk of a mile along some shores ordinarily will show several types of shore environment and almost every kind of mechanical sediment. Lime muds, shell matter, and logs and seaweeds are more or less common littoral materials, and on many low shores these dominate. The shores of some of the Paleozoic epicontinental seas bordering lands which had been reduced to base level probably had uniformity of deposits, and it is considered likely that such extensive black shale formations as the Chattanooga represent a variety of littoral deposit made under such conditions in seas with weak tides.

In general, the deposits of the littoral environment consist of boulders, gravels, sands, muds, and shells and shell fragments, each grading into another alongshore and grading outward by more or less insensible stages into the deposits of the neritic environment. Shores bordering low lands may have the sediments largely calcareous or organic. The original colors of the mechanical sediments of the littoral environment are light to dark gray unless the composing rock particles are differently colored. Organic sediments range from white to black.

The deposits of the littoral environment may be mud cracked, but, except locally, the conditions are not particularly favorable for mud-crack development. Rain impressions and the markings of similar appearance may be present, as most of the agents responsible for such markings are in almost

[128] Andrée, K., Geologie des Meeresbodens, Bd. 2, 1920, pp. 30–118. A rather complete consideration of the processes and phenomena of the strand is given in this work.

daily operation in this environment. Ripple mark may form on every surface, and both symmetrical and asymmetrical types may be present, the latter the more common. The strong wave activity produces much cross lamination. The littoral environment is the feeding ground for many land animals, and these leave their tracks on the sands and muds, and marine organisms leave their burrows in the deposits, these being tubes of various kinds, from the U-shaped tubes made by *Arenicola* to the nearly vertical tubes made by *Mya*, some crabs, and certain of the worms. The draining of water from the sands and muds of the littoral following retreat of the waves and the tides produces dendritic rill markings and on some sands the series of diamond-shaped markings described on page 671. The expulsion of air from sands by incoming waves produces the numerous sand holes.

Littoral deposits for any single position of sea level cannot attain a great thickness, as such is limited by the tidal range. Rise of sea level may produce a greater thickness. The rise of sea level may move the littoral environment inland or build a new littoral deposit upon the old, the results depending upon the strength of the waves, which in turn depends upon the depth of water in the neritic zone. If shallow water exists for a long distance outward from the shore, little inland movement is likely, and a new littoral deposit may be superimposed directly on the old. If considerable depth of water exists adjacent to the shore, the previous littoral deposit is likely to be more or less reworked to form a part of the deposits of the neritic environment, and a new littoral deposit built inland from the old. The former condition has as an invariable accompaniment deposits of mud and sand, the muds not infrequently carrying considerable organic matter, and it is suggested that some of the black shales formed under such conditions. A great thickness is possible, depending upon the relations between rise of sea level and building up of the bottom. If a new littoral deposit is built inland from the old, the deposits consist mainly of sands and gravels. The thickness of the littoral deposits made under these conditions is small, and it seems probable that the combined thickness of coarse materials of the littoral and neritic environments is not likely to exceed 100 feet, and Barrell expressed the opinion that the possible thickness would be considerably less than 100 feet.[129]

Criteria for the Determination of Littoral Deposits

The stratigraphic positions of deposits of the littoral environment are at the base and the top of each marine deposit made between an advance and retreat of the sea. The deposits at the top have little chance of being pre-

[129] Barrell, J., Some distinctions between marine and terrestrial conglomerates, Bull. Geol. Soc. Am., vol. 20, 1909, p. 620; Criteria for the recognition of ancient delta deposits, Ibid., 23, 1912, p. 441.

served,[130] and those at the base may be partly or wholly reworked and more or less incorporated in the neritic deposits. Littoral deposits may be mud cracked and may contain "rain prints," rill marks, sand pits, ripple marks, and tracks of land and water animals. Coarse materials have irregular stratification and are likely to be cross-laminated. Shells of marine animals may be common, and some land animal remains are probable, both generally in a fragmentary condition. Fine sediments may be evenly laminated and may contain shells and other organic materials in an excellent state of preservation.

Relative Importance of Littoral Deposits

Quantitatively, littoral deposits made in waters with strong waves have little significance. They are not thick at any time of their existence, and as they are progressively buried, the thickness is decreased and in many instances reduced to nothing. Their importance lies in the fact that they record positions of the shorelines. Littoral deposits made in waters with weak wave action may, on the other hand, attain considerable thickness and cover extensive areas.

Littoral Deposits in the Geologic Column

Deposits which are either those of the littoral environment or the upper portion of the neritic are common in the upper Mississippi Valley and elsewhere at the base of the Cambrian. The different geologic systems have similar deposits on one or more levels, as that between the Beekmantown and Chazy of the northern Appalachians, the base of the Pennsylvanian west of the Mississippi River, the base of the Lower Cretaceous of Texas, etc. If some of the black shale and other formations were deposited in the littoral environment, it follows that the occurrences are more extensive than generally supposed. Scott[131] interprets the Woodbine sands of the Texas Cretaceous as due to a retiring sea, from which it follows that a part of them may be of littoral origin.

THE DELTA ENVIRONMENT AND ITS SEDIMENTS

Following Barrell,[132] a delta is defined "as a deposit partly subaerial built by a river into or against a body of permanent water." A delta results

[130] Scott, G., The Woodbine sand of Texas interpreted as a regressive phenomenon, Bull. Am. Assoc. Pet. Geol., vol. 10, 1926, pp. 613–624. Scott presents evidence supporting the view that the Woodbine sands were left by a retiring sea.

[131] Scott, G., op. cit., 1926.

[132] Barrell, J., Criteria for the determination of ancient delta deposits, Bull. Geol. Soc. Am., vol. 23, 1912, pp. 377–446. This article has been extensively used in the preparation of this topic. Studies of the sediments of the Mississippi delta have been made by Professor A. C. Trowbridge and his assistants. These studies have not been published.

when a stream supplies more material than can be handled by the waves and currents of the body of water into which it empties. Deltas may be built into lakes and rivers, and such are continental deposits. They resemble deltas built into the sea except as the latter are modified by the presence of marine factors.

The Components of Deltas

The deposits made in deltas are partly subaerial and partly below the surface of the permanent body of water into which a stream empties. The subaerial deposits are fluvial, lacustrine, and paludal. The subaqueous deposits are partly of stream deposition and partly of marine or lacustrine, depending on whether the permanent body of water is the sea or a lake.

Deposits are made on a delta's upper surface, in the channels which cross it, on its front, and over the bottom beyond its front. The deposits on its upper surface are known as the topset beds. These are essentially flat-lying, although they may slope gently from the drainage lines over the subaerial portions and seaward over those which are subaqueous. The deposits over the delta front are known as the foreset beds. These have a wide range in their inclinations, sloping at high angles in small bodies of water with weak wave and current action, and at low angles in large bodies with vigorous waves and currents. The deposits made beyond a delta's front are known as the bottomset beds. These are composed of fine materials and are essentially flat-lying. The three components are readily differentiable in deltas made in the laboratory and those of small lakes. In large deltas the conditions are so extremely complex that they may not be apparent. In a large way, however, they should be present.

The topset beds are either subaerial or subaqueous. The subaerial deposits are made on the subaerial delta plain, or that part of the delta which is exposed except when covered by stream flood waters or the waters of great sea waves and tides, and in the channels which are cut across this plain. The sediments on the surface of this plain are deposited by floods, by the stream in its channels, and in delta lakes and swamps. In dry regions wind may also assist in deposition. Near the outer margin of the subaerial plain waves may raise barriers which in turn create lagoons. The waters of these lagoons may be either fresh or salty, the more common occurrence being alternating conditions of longer or shorter duration. If waves are weak and shallow waters extend a long distance outward from the shore, barriers seem unlikely, and there are no lagoons but a gradual passage of salt waters and a characteristic plant life into a fresh-water marsh environment.

The subaerial delta plain is the delta of the geographers, but from the

point of view of the sedimentationist it is but one part of a connected deposit. It may be more or less separated from the subaqueous plain or submerged part of the topset beds by the shore face, and it grades upstream without break into the flood plain, from the deposits of which its own may differ in no important particulars.

The deposits of the subaerial plain are extremely variable, both horizontally and vertically. Fluvial, lacustrine, paludal, and lagoonal sediments may occur on many levels and in most vertical sections. Mud cracks and "rain print" markings may be present locally. Both are common on the subaerial plains of dry regions. Slumping of sediments due to settling, undermining, and other cases should be more or less common. There are great variations in the extents, thicknesses, colors, markings, materials, and structures of the sedimentary units.

The organic remains in the deposits of the subaerial plain are mostly of terrestrial origin, and root structures and plants in place may be present. Remains of marine animals may be carried in by birds and other land animals; an occasional large marine flood may sweep marine organisms for long distances over the surface of the subaerial plain; and marine organisms not uncommonly may be brought into tidal channels and delta lakes at times of high tides.

The shore face separating the subaerial from the subaqueous plain is a result of stream deposition or is formed by the waves. Its extent and shape largely depend upon the vigor of wave action. Where wave action is strong, the slope may be steep and relatively high, and in some cases there may be a barrier beach. Where the waves are weak with respect to the stream currents, the shore face is relatively insignificant and its position indeterminate, as the sea bottom may gradually pass into a swamp area. The shore face and associated intertidal zone have the characteristics of the littoral environment. The position of the shore face in a geologic section may be determined by the fact that it separates the sediments of stream deposition from those of standing water, and by the further fact that the organisms in the deposits of the landward side are dominantly terrestrial and those on the water side are partly marine or lacustrine. It is obvious that great difficulty would attend accurate determination of the position of the shore face.

The subaqueous plain slopes gently outward into deeper waters at inclinations determined by the conditions. The sediments upon it are laid down by waves and marine and stream currents, and they have the characteristics of sediments so deposited. The waters over this plain range from fresh to salt, the salt content varying seasonally with the tides, the direction and strength of the winds, and the positions and discharge of the distributaries

on the subaerial portion of the delta. The sedimentary units are more or less discontinuous, particularly on the landward margins. Inclinations and coarseness should decrease outward in directions radial to the mouths of the distributaries. The deposits may contain terrestrial and fresh-water organisms, but root structures and plants in natural position are not present, although stumps with roots attached may assume an upright position when they come to rest and thus appear to be in place.[133] Marine and brackish-water organisms are present to a greater or less degree, particularly in the deposits made between the distributaries.

The foreset slope receives the deposits known as the foreset beds. Both river and marine waters are concerned in their deposition, the former adjacent to the ends of the distributary currents and the latter over the intervening areas. The coarsest materials of a delta may be found here (channels in the subaerial plain excepted), and they may be deposited with considerable initial inclination. Streams flowing into quiet bodies of water and carrying coarse material usually have high angles of initial inclination in the foreset deposits. In large bodies of water the angles of initial inclination usually are low. The upper portions of the foreset beds are deposited above wave base; the lower portions may be below that level. The sediments are mostly muds and sands. Lime sediments are not common, and peat formed in place does not occur. The deposits contain remains of marine organisms, particularly between the distributaries. Terrestrial and fresh-water organic remains may occur in the deposits adjacent to the mouths of the distributaries. The areas of the subaqueous topset beds and foreset beds have great environmental instability. The mouths of the distributaries undergo considerable shifting, and the quantity of water discharged by the streams is subject to much variation. A shift of a distributary leads to the discharge of fresh water upon areas where previously the waters may have been salty. Great destruction of the marine organisms of these areas would necessarily follow. Floods like that of the Mississippi River in 1927 displace much salt water about the mouth of a stream, with much destruction of marine life. Denison[134] has called attention to such destruction on the coast of India during times of great discharge from rivers consequent to rainfall connected with the southwest monsoon.

The bottomset beds are deposited largely under marine conditions and for the greater part consist of fine suspended and colloidal materials which owe their precipitation largely to the action of electrolytes in solution or colloids of opposite sign. The beds range outward to extreme thinness and

[133] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv., Canada, 1921, p. 38.

[134] Denison, W., Quart. Jour. Geol. Soc., vol. 18, 1862, p. 453.

are deposited in essentially horizontal position. They do not greatly differ from other fine deposits made in marine waters of similar depth and character.

As a delta advances, the subaerial plain is built over the subaqueous plain, the latter over the foreset beds, and the bottomset beds are progressively covered by sediments of foreset deposition. Thus, a vertical section through a delta deposit should have bottomset beds at the base succeeded upward by foreset beds, sediments of the subaqueous plain, and at the top sediments of the subaerial plain.

From what has been said it should not be inferred that the deposits of the different parts of deltas are sharply defined. It is possible for materials as coarse as those found anywhere in a delta to be deposited with the bottomset beds. The material precipitated by flocculation is deposited in the delta channels, in the bays between the distributaries, and during low-water stages over the foreset slopes as well as over the bottomset portion of a delta. Gravels do not seem to be common in large delta deposits, but they may be present. In the Los Angeles Basin section the Pliocene Pico formation strongly suggests the delta environment. Its total thickness exceeds 12,000 feet. It contains beds of gravels, the average diameters of which average about an inch, but dimensions range to a foot. The gravel beds are 5 or more feet thick; the rock particles are round to angular; and they are in a sand matrix. The beds are very lenticular, lens out from the source of supply, are characterized by cut-and-fill structure, are separated by cross-laminated sands and lignitic clay, and marine fossils occur in some of the beds.[135] The gravels probably are present because of nearness of deposition to distributive areas.

Streams emptying into bodies of water of which the waves and currents have energy sufficiently ample to dispose of all sediments which may be brought have no subaerial plain, as the sediments are distributed outward and alongshore to greater or less extents. These sediments are not greatly unlike those of the subaqueous portions of deltas with subaerial plains and foreset and bottomset beds, except, perhaps, in containing a greater abundance of marine fossils.

The Nile delta illustrates the topographic features of large deltas.[136] The subaerial plain is dotted with lakes and swamps, and about its seaward margin are many lagoons. Tortuous distributaries find their way through this plain to the Mediterranean. The shore face extends to depths of 6 to 10 meters, as shown by the closeness of these depths to the shore. The

[135] Cartwright, L. D., jr., Sedimentation of the Pico formation in the Ventura Quadrangle, California, Bull. Am. Assoc. Pet. Geol., vol. 12, 1928, pp. 235–270.

[136] Barrell, J., op. cit., pp. 387–389.

subaqueous plain extends outward to a depth of 200 meters. The depth of 50 meters is attained at a distance of 50 km. from the shore, and to this depth the slope is very gentle. The surface then descends rapidly to 200 meters and then still more rapidly to 1000 meters, the slope from 50 to 200 meters being in the nature of a transition zone between the subaqueous plain and the foreset slope. The latter is considered to extend from depths of 200 to 1000 meters and has an inclination of about 1.5°. The bottomset beds lie at depths of 1000 to 2000 meters and show their presence in outward convexity of the submarine contours. Studies made by Judd[137] of deposits in the subaerial portion of the delta indicate that the chief constituents are sands and silts. The sands are mostly quartz, but contain more or less feldspar, mica, and small percentages of rarer minerals. The silts contain little clay or kaolin, but the chief constituents are small particles of quartz, feldspar, mica, and other minerals. The mineral particles are dominantly fresh.

Within recent years the somewhat youthful delta of the Fraser River of British Columbia, Canada, has been studied in detail by Johnston, and much has been learned of the component parts of this delta and the characteristics of its deposits.[138] The following description is slightly modified after that of Johnston (1922, pp. 119–120).

> The inclined foreset beds forming the subaqueous front are well developed and extend from the 3-fathom line to about the 30-fathom line and have an average dip of about 10 degrees. The dip, however, is irregular and in places the subaqueous front of the delta is nearly vertical for heights of 1 to 3 fathoms. Below the 30-fathom line the beds slope gradually seaward, the 100-fathom line being reached at from 1 to 2 miles from the outer edge of the sand banks. The horizontal bottom-set beds, consisting of very fine material, form a considerable part of the floor of the strait of Georgia off the entrance of the river. . . The horizontal top-set beds forming the upper part of the delta are thinnest and in most places are only a few feet thick. In some places, as in the deep abandoned channels of the river the thickness may attain more than 100 feet. The top-set beds are sandy to high tide level; above they are silty and the silty, fine-grained beds formed from deposition of flood waters overflowing the banks, become progressively thicker upstream. The shore face of the delta is feebly developed because wave action has little effect, owing to the shallowness of the water over the sand banks.

The subaqueous topset beds are composed of sand and silt, the latter evenly and thinly laminated, the laminations being due to tidal action. Banding interpreted as seasonal is indicated in places by layers of vegetable matter and by tidal laminations formed during the freshets when the sedi-

[137] Judd, J. W., Report on a series of specimens of the deposits of the Nile Delta, obtained by the recent boring operations, Proc. Roy. Soc. London, vol. 39, 1885, pp. 213–227.

[138] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Surv. Canada, 1921; The character of the stratification of the sediments of the recent delta of the Fraser River, Jour. Geol., vol. 30, 1922, pp. 115–129.

ments are mostly silt and at low water when they are mostly fine sand. The supposed seasonal layers average five to six to a foot. The record is not complete, as every section shows evidence of contemporaneous erosion.

The lower part of the top-set beds, exposed at low tide in the seaward part of the delta, is dominantly sandy, but contains in places thick beds of silt and clay. These beds are not definitely laminated and are lenticular in outline. They are usually compacted and offer greater resistance to erosion than the sandy beds, which are in part horizontally bedded and in part crossbedded and current ripple-marked. In places shell beds or dead shells of marine species occur embedded in the sand and silt. They are most abundant at about the contact of the upper silty beds and the underlying sandy beds. They occur in the bank of the river at Steveston and in the seaward part of the delta near the shore face.

The core samples from the subaqueous part of the delta in the strait of Georgia showed that the foreset beds off the main mouth of the river are thinly but irregularly laminated. The lamination is somewhat similar to that of the tidal flood-plain deposits, but is more irregular and is in places markedly crossbedded. This bedding is also tidal, but is the result of the combined effects of flocculation, river and tidal currents, and slack water.

The core samples from depths of 50 to 100 fathoms in the strait of Georgia showed that the bottom-set, fine-grained beds, occur in massive, thick beds, in which no definite stratification is visible to a depth of at least 2 feet.

In this absence of lamination the bottomset beds differ from the fine-grained sediments which are being deposited in the fresh waters of Pitt Lake on the delta. The color of the bottom sediments is uniformly gray. Beds of black silt and clay occur in those parts of the topset beds in which dead shells are abundant. A well drilled on the delta shows the deposits to have a thickness of at least 700 feet.

Development of the Components of Deltas

The development of the components of deltas varies with the size and depth of the water, the character and abundance of sediments, the extent of the delta front, the vigor of the waves and currents, the velocity and volume of the water in the streams, and the movement of sea level.

Strong ocean currents and waves and fine waste give wide distribution of sediments and extensive development of the bottomset beds as compared to the other components. These conditions obtain about the mouth of the Mississippi, as the waste carried is fine and the waves and currents about the delta front strong. Streams emptying into bodies of water of which the waves and currents have energy sufficiently ample to dispose of all sediments brought may have no subaerial plain, as the sediments may be entirely distributed. Deep waters about a delta front with constant sea level and weak wave and current action lead to the deposition of most of the waste in the foreset beds. The deltas of the Ganges and Brahmaputra rivers illustrate these conditions except that waves and currents are by no

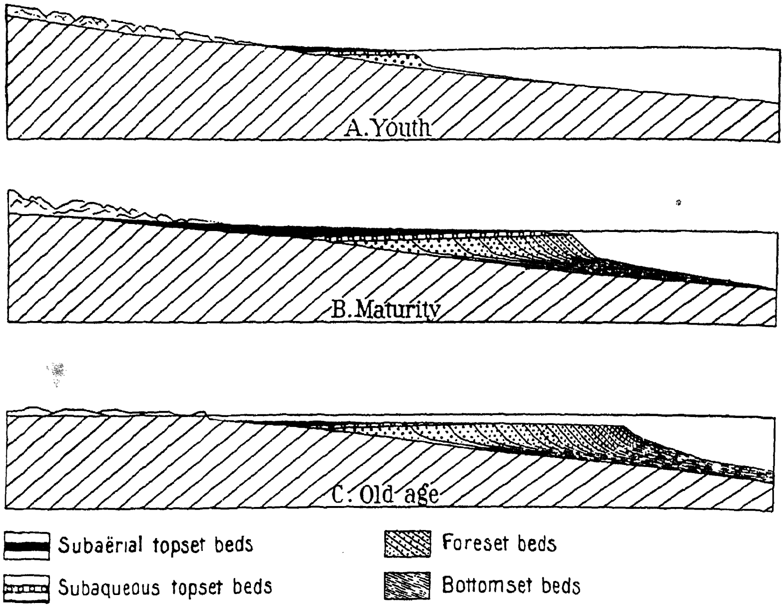
means weak. Strong wave action, moderate depth, great extent of delta front, and a slowly rising sea level favor the development of a wide subaqueous plain. These conditions are thought to obtain about the delta of the Nile. Weak waves, coarse and abundant sediments, stationary or falling sea level, and several rivers converging toward a shallow sea lead to the development of an extensive subaerial plain. The compound delta of the Rhine and adjacent rivers illustrates these conditions. Other combinations of the factors lead to other results.[139]

The Delta Cycle

The development of the three components of a delta is closely related to the physiographic age of the country drained by the forming stream. In physiographic youth a stream usually supplies more waste than the waves and currents of the stationary body of water can distribute. The excess is left at the mouth of the stream to form the delta. With extension of a stream into the region drained the excess of waste may increase to a maximum, and during this period of increase the delta continues to advance, but each advance widens its front and renders it more accessible to wave and current attack. Following the time of supply of maximum waste, a decline sets in, culminating in old age of the physiographic cycle when the waste supplied is so small in quantity as to be negligible. At some time in this decline, probably about late maturity of the physiographic cycle, the quantity of waste supplied is equal to that which can be handled by the waves and currents, and further decline leaves an excess to these abilities. This excess energy is devoted to removal of some parts of the delta to a level and profile determined by the conditions. Most, if not the whole of the deposits of the subaerial plain, large parts and perhaps the whole of the deposits of the subaqueous plain, and possibly the upper portions of the topset beds, particularly on the seaward margin, may be removed. A plain of erosion results. The time involved in the building and destruction of the delta to the extent described is the delta cycle (fig. 118).

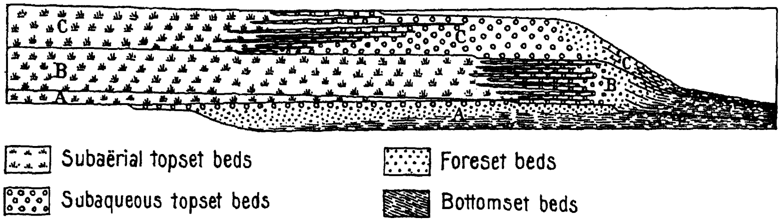
The above statement of delta history assumes a stationary sea level. If sea level is not stationary, the results are different. If sea level slowly rises with respect to the delta surface and there is no increase in the supply of waste, the subaerial plain attains slight development, and there is a great development of the subaqueous plain whose topset beds attain a thickness proportionate to the rise of sea level. If the rise of sea level is accompanied by elevation of the region from which the stream derives its sediments, the distributive area, sufficient waste may be supplied to enable the stream to

[139] See Barrell, J., op. cit.



Vertical scale magnified several hundred times

FIG. 118. ILLUSTRATING THE DELTA CYCLE
After Barrell



Vertical scale magnified several hundred times

FIG. 119. RELATION BETWEEN DELTA BUILDING AND SUBSIDENCE

A. First stage: Delta built out into water of constant level; basin deeper than base level of deposition. No subsidence. Shows initial dominance of foreset beds, increasing importance of topset beds, shallowing of the basin, and decreasing importance of foreset beds.

B. Second stage: Intermittent subsidence balanced by deposition. Delta built upward rather than outward with dominance of topset beds.

C. Third stage: Subsidence at a faster rate, maintaining a larger ratio of subaqueous topset beds. After Barrell.

build a subaerial plain. The progressive but intermittent rise of sea level will repeatedly extend the sea over the subaerial plain and lead to marine deposits thereon, over which there will then be deposited the sediments of the three components of the delta as it advances during the period of stability. The result is a dovetailing of marine and delta sediments, the extent of each varying with the conditions. Each marine and each delta unit may be bounded by unconformities (fig. 119). If the movement of sea level is oscillating, each rise brings in the sea; each fall moves it outward, extends the foreset beds, and erodes the subaerial and subaqueous plains. A section from a boring made in the subaerial plain of the Mississippi delta between the river and Lake Borgne at a distance of 15,000 feet from the river shows what may be expected and is as follows:

	feet
Soft dark brown mud, many fresh-water and a few marine shells	10
Fine blue clay, fresh-water origin	14
Coarse gray sand, fresh-water origin, except possibly base	16
Sand and clay mixed, probably fresh-water origin	10
Blue clay, contains marine shells	14
Sands, contain chips from a log and marine shells	9
Blue clay with marine shells	7
Sand and blue clay with marine shells	11
Blue clay	9 [140]

It is not known to what depth the bottom materials extend.

Summary of Delta Deposits

Deposits are of four classes: the topset deposits of the subaerial plain, the topset deposits of the subaqueous plain, the deposits of the foreset slope, and the bottomset beds beyond the foreset slope.[141] The deposits of the subaerial plain are of continental origin, are decidedly lenticular, show much channel cutting, are locally mud cracked and marked with "rain prints," locally contain the tracks of land animals, and have in greater or less abundance the remains of land and fresh-water animals and plants, some of the latter occurring in places where they grew. They exhibit various degrees of oxidation and reduction and hence have colors related to the quantity of organic matter they contain and the degree of oxidation. The color in some cases is black, in others gray, yellow, and red. Sorting and stratification tend to be poor and irregular, although each may be locally excellent. Many strata are cross laminated, and contemporaneous deformation may

[140] Hilgard, E. W., and Hopkins, F. V., Ann. Rept. Chief Eng., War Dept., App. W 2, 1878, pp. 855–890.

[141] Trowbridge, A. C., Personal communication, suggests that undue emphasis has been placed on these distinctions. The present writer agrees with Trowbridge, but the distinctions, as made, serve to emphasize the differences in environmental conditions.

be not uncommon. The sediments consist of sand, silt, clay, and vegetable matter. Beds of lime sediments are not likely to be present, although much lime may occur throughout the sediments. Gravel seems to be uncommon, but may be present. Marine fossils may be present to a greater or lesser extent.

The sediments of the subaqueous plain are deposited by the waters of the distributaries and waves and currents of varying direction and vigor. The units are usually lenticular and have uneven stratification, although regularity of stratification may obtain over extensive areas. Both land and fresh-water organisms may be present, but no land plants will be found in the places of growth, although stumps with attached roots may come to rest so as to appear in place. The sediments consist of clay, silt, sand, and occasional accumulations of vegetable matter. Beds of calcareous material are rare, and such seems also to be the case for gravels. Contemporaneous deformation may be common. The most common colors are gray and blue.

The sediments of the foreset slope are deposited by waves and currents and the waters of the distributaries. Some of the depositing water may be salty, or at least brackish, leading to flocculation of the fine sediments. The sediments may be poorly sorted and stratified, and the beds may have considerable initial inclination. Marine or lake fossils are commonly present, and organic matter of land or stream origin is not uncommon. Gray and blue colors dominate. The bedding is inclined fan-shaped from the distributary mouths, and considerable contemporaneous deformation may be associated with strata of high angles of initial inclination. The materials consist of clays, silts, sands, and some lime sediments.

The bottomset beds are deposited under marine conditions, although the materials are of stream derivation. The materials range from fine sands to silts and clays.

The deposits of the delta environment may attain thicknesses of many thousands of feet, dependent upon the depth of the body of water in which they are made and the extent of settling of the base upon which deposition takes place. Andrée[142] following Credner[143] seems to incline to the view that delta deposits attain slight thickness, but this statement seems to apply only to that part of delta deposits which are of subaerial deposition and even then it seems of doubtful validity.

Subaqueous delta sediments dovetail with each other, and no sharp distinctions exist. Studies of sediments carried into the Gulf of Mexico by the Mississippi through Southwest Pass indicate: (1) That the largest

[142] Andrée, K., Geologie des Meeresbodens, vol. 2, 1920, pp. 121–122.

[143] Credner, G. R., Die Deltas, Ergänzungheft, no. 56, Petermann's Mitth., 1878.

particles range from $\frac{1}{4}$ to $\frac{1}{2}$ mm. in diameter and that these are deposited on the crest of an offshore bar or in the beaches on the sides of the Pass lands and that few particles exceeding $\frac{1}{8}$ to $\frac{1}{4}$ mm. in diameter are carried outward farther than 5 miles. (2) That the sediments of the offshore bar are coarser than those of any of the beaches and that the finest sediments are in the deepest water southwest of the Pass mouth. (3) That 22 miles straight out from the Pass mouth there is an area over which the water is 32 fathoms deep (water nearer the Pass mouth having a depth of 50 fathoms), over which the sediments are coarser than on bar or beach and do not seem to have been contributed by the present river. (4) That the particles are angular, are of varied mineral content, and contain glauconite on the outer steep slope. (5) That except for shell fragments an area about the mouth of about 3 miles radius appears to be without life and organic remains, a zone 3 to 8 miles out contains agglutinate and chitinous foraminifera, beyond this there are calcareous foraminifera, and beyond 10 miles pelagic forms constitute a part of the bottom sediments.[144]

No one single characteristic can be relied upon to determine that a deposit was formed in the delta environment, as each of the characteristics to which reference has been made may develop in any one of several other environments. The aggregate of characteristics coupled with the relations of the components of a deposit to each other and to the deposits of adjacent environments is essential. Many marine deposits may show every feature which is found in the sediments of the bottomset, foreset, and subaqueous topset beds. Marine deposits may be similarly cross laminated, contain the same fossils, and have the same mineralogical and lithological constituents.

Deposits of Ancient and Modern Deltas

Due to the various movements of Pleistocene and Recent time, existing streams seem to be more or less out of adjustment to sea level, and, in general, conditions do not seem to be particularly favorable for the extensive development of the subaerial parts of deltas. Many large rivers, as the St. Lawrence, Amazon, and Congo, have this component lacking or feebly developed. Nevertheless, subaerial delta plains constitute extensive areas of the present land surface. The subaerial plain of the delta of the Ganges and Brahmaputra rivers has an area approximating 50,000 square miles; that of the Nile is about as large; that of the Hoang Ho is of greater extent; and other large delta plains are those of the Rhine, Mississippi, Orinoco, Colorado, Indus, and Yukon. In addition there are scores of smaller delta plains, and it is not improbable that over a half million square miles of the present land

[144] Trowbridge, A. C., Disposal of sediments carried to the Gulf of Mexico by Southwest Pass, Mississippi River Abstract Bull. Geol. Soc. Am. vol. 38, 1927 p. 148.

surface are underlain by the subaerial deposits of deltas. As the submerged portions of deltas are as large, and probably larger than the exposed portions, the total present area receiving deposits of the delta environment may aggregate around 2,000,000 square miles.

During those times of the geologic past when shallow seas covered vast areas of the continents and highland regions bordered the seas, ideal conditions existed for the development of large deltas. If the regions of supply of sediments were being elevated and the sites of delta deposition were sinking, great thickness of delta deposits would be possible. That this has occurred during several periods of geologic time is certain.

Barrell[145] has shown that the lower portions of the Cretaceous formations of the Atlantic coast are best interpreted as of delta origin, and Barton[146] has presented evidence to the effect that the materials forming the coastal portions of southeast Texas were deposited in a coalescent delta of probably late Pleistocene time formed by the Trinity and Brazos rivers. The Catskill formation of New York and along the Appalachians to the south is the delta deposit of a late Devonian river,[147] apparently accumulated under conditions of a slowly rising sea level. The Coal Measures of Indiana and Illinois are best interpreted as deposits made in the delta environment under conditions of progressive, but intermittent, rises and occasional falls of sea level, many streams probably contributing to form the deposits. The sediments consist largely of lenticular yellow sandstones, some of which are micaceous, and shales of different colors, but with yellow, gray, and blue dominating. Coal beds occur at several horizons, and mud cracks are common. Few strata persist for long distances. At several levels are widespread layers with marine fossils. These marine beds commonly are limestones and record a rise of sea level with wide invasion of marine waters over a flat delta surface. The Coal Measure deposits of southwestern Indiana appear to be largely those of the subaerial plain. True foreset beds seem to be rare.

The Coal Measures of Kansas, Missouri, and Oklahoma were also largely deposited under the condition of a delta environment, but they differ from those of Indiana and Illinois in that the sea made many invasions, and thus considerable parts of the sequence are marine. The rise of sea level was intermittent and unequal, as shown by the variations in thickness of the deltaic and typically marine formations. This is illustrated by the Weston

[145] Barrell, J., Criteria for the recognition of ancient delta deposits, Bull. Geol. Soc. Am., vol. 23, 1912, pp. 406–411.

[146] Barton, D. C., Surface geology of coastal southeast Texas, Bull. Am. Assoc. Pet. Geol., vol. 14, 1930, pp. 1301–1320.

[147] Barrell, J., The Upper Devonian delta and the Appalachian geosyncline, Am. Jour Sci., vol. 36, 1913, pp. 429–472; vol. 37, pp. 87–109 and 225–253.

shale, Iatan limestone, Lawrence shale, and Oread limestone formations. Each of the two shale formations consists of sandstones and shales and has a thickness of 150 feet or more. The Oread limestone, consisting of three limestone members separated by shale members, has a thickness approximating 50 feet. The Iatan limestone in most places is under 10 feet thick. The Weston and Lawrence formations appear to be largely of topset deposition, as they are without marine fossils, contain an abundance of plant remains, and have local lenses of coal. The Weston formation appears to have been built into a shallow sea. A rapid rise of sea level flooded the surface of the Weston delta and led to the deposition of the Iatan limestone. The Lawrence shales were deposited as a delta over this limestone. Another rise of sea level led to the deposition of the Oread formation.

The great pile of Pennsylvanian sediments north of the old land of Llanoria in Texas and Louisiana seems best interpreted as partly deposited in the delta environment with the subaerial phase dominating. The Pennsylvanian deposits of north-central Texas are referred to the same environment, but with a greater development of subaqueous deposition.[148]

Great thicknesses of the Pennsylvanian of the Appalachian geosyncline seem to have accumulated in the delta environment, and delta building was in progress in the Appalachian geosyncline at one place or another throughout the entire period. Schuchert states that three fresh-water deltas formed in this trough, one in the vicinity of Pottsville, Pennsylvania, a second in the Kanawha valley of West Virginia, and a third in the Cahaba valley of Alabama.[149] Branson[150] has described a delta deposit from the Mississippian of Virginia.

Considerable portions of the Cretaceous strata of Montana, Wyoming, and Alberta along the western borders are best interpreted as ancient delta deposits made by streams flowing into the Cretaceous sea from land areas to the west. The sediments consist mostly of muds, silts, and sands, and it is thought that every component part of deltas may be identified, fine dark muds with marine fossils representing the bottomset beds, foreset cross-laminated sandstones containing marine and terrestrial fossils, and shales and sandstones with coal beds and terrestrial plants representing the deposits of the subaerial and subaqueous plains.[151] Berry[152] has called

148 Honess, C. W., Geology of southern Le Flore and northwestern McCurtain counties, Oklahoma, Oklahoma Bureau of Geology, cir. no. 3, 1924; Miser, H. D., Llanoria, the Paleozoic land area in Louisiana and eastern Texas, Am. Jour. Sci., vol. 2, 1921, pp. 61–89.

149 Schuchert, C., Text book of geology, pt. ii, Historical geology, 2nd ed., 1924, p. 354.

150 Branson, E. B., A Mississippian delta, Bull. Geol. Soc. Am., vol. 23, 1912, pp. 447–452.

151 Bowen, C. F., Gradation from continental to marine conditions of deposition in central Montana during the Eagle and Judith River epochs, Prof. Paper 125–B, U. S. Geol. Surv., 1919.

152 Berry, E. W., The delta character of the Tuscaloosa formation, Johns Hopkins Univ., Cont. to Geology, 1917, pp. 18–24.

attention to the probability that the sediments of the Tuscaloosa formation of Misssissippi, Alabama, and parts of some adjacent states were deposited in the delta environment.

The Huronian and Keewatin deposits of the Lake Superior region in part appear to have developed in the delta environment, and some parts of the Keweenawan may have had this origin.

The Tertiary Ione formation of the Great Valley of California, consisting of quartz sands and gravels, clays, and beds of lignite, was assigned by Allen[153] to an environment about the mouths of many streams flowing from land to the east, that is, it is a compound delta deposit. The Pico formation of the Los Angeles Basin seems to be of delta origin.

Strata of delta origin seem to be equally abundant on other continents. The Weald of the Cretaceous of southeast England and the Estuarine series of the Jurassic of Yorkshire[154] have been referred to an origin in this environment. The Estuarine series is said to show filled channels, washouts, deposits of lagoons, and the topset and foreset deposits of a delta. The Millstone Grit[155] is referred to delta origin, the delta having been made by a large river draining from the north with tributaries flowing over different kinds of rocks. Parts of the Molasse and Flysch of the Cretaceous and Tertiary of the Alpine region and some of the Tertiary of the London and Paris basins seem to be of deltaic origin.

The Tertiary of the Irrawaddy Basin of Burma seems to be composed of delta deposits that filled an ancient Burmese gulf under conditions of fluctuating sea level.[156]

THE MARGINAL LAGOON ENVIRONMENT AND ITS SEDIMENTS

The marginal lagoon is a small body of water which has been partially separated from a larger body by the building of a bar or barrier beach, connection with the parent body being maintained by one or more openings. The lagoon differs from the shore lake in its more intimate connection with the parent body. Along parts of the southern coast of the Gulf of St. Lawrence a lagoon is known as a *barachois* and the opening as a *tickle*. In the

[153] Allen, V. T., The Ione formation of California, Univ. California Publ. Geol. Sci., vol. 18, 1929–30, pp. 347–419 (402–406), pls. 24–37.

[154] Black, M., Drifted plant beds of the upper Estuarine series of Yorkshire, Quart. Jour. Geol. Soc., vol. 85, 1929, pp. 389–439.

[155] Gilligan, A., The petrography of the Millstone grit of Yorkshire, Quart. Jour. Geol. Soc., vol. 75, 1919, pp. 251–294.

[156] Stamp, L. D., An outline of Tertiary geology of Burma, Geol. Mag., vol. 59, 1922, pp. 481–501; Geology of the oil fields of Burma, Bull. Am. Assoc. Pet. Geol., vol. 11, 1927, pp. 557–579; Cotter, G. de P., The geotectonics of the Tertiary Irrawaddy Basin, Jour. Asiatic Soc. Bengal, vol. 14, 1918, pp. 409–420. Stamp refers to other papers relating to these delta deposits.

old-age stage of the lagoon cycle the lagoon may become a marsh, or the bar may be removed by wave erosion, and complete connection with the parent body be reestablished. Consideration of the lagoon environment is limited to those connected with marine waters.

The waters of a lagoon range from fresh to salt, and the concentration in places may exceed that of the adjacent sea. Normally fresh water is brought by streams, and the quantity at times may be so large as to exclude the entrance of much salt water. Certain areas may be overlain by salt water at all times, and other areas by fresh water. As salt waters are heavier than fresh, the former may enter a lagoon as subsurface currents, and the fresh waters contributed by streams may be confined entirely to the surface over some parts of a lagoon. The different concentrations influence the temperatures of the waters.

The variations in salinity, both laterally and vertically, and those in temperature determined by salinity and other factors may control and certainly do influence the distribution of organisms, leading to considerable variation in the organic assemblages over different parts of a lagoon. In places of repeated and decided changes in salinity, organisms may be altogether excluded, and in other places too great or too little concentration may dwarf many forms. As noted later, there are other conditions in certain lagoons which may result in dwarfing. Over some areas the bottoms may be densely populated with marine forms, and over others the organisms may be those of the fresh water. Some places may support a marine fauna in the lower waters and possibly fresh-water organisms in the upper levels. The quiet waters encourage the growth of considerable bottom and floating vegetation, the presence of which will bring in organisms adapted to the plants concerned.

The sediments may exhibit considerable range. Terrigenous sediments are brought by the streams and winds and carried in by currents from the sea, and materials of organic derivation and chemical precipitation are produced *in situ*. The terrigenous sediments range from clay to sand and perhaps particles of larger dimension. The currents from the sea may bring in some shell and plant matter and particularly planktonic organisms, the latter perhaps being killed on contact with fresh water, and thus becoming buried in the deposits of an environment to which the organisms were not adapted. Calcium carbonate is precipitated by green plants, by invertebrates, and probably by other agents. As the waters in the deeper parts of the bottom may become stagnant, such places are likely to become filled with black muds containing abundant anaërobic bacteria, among which the so-called sulphur bacteria are likely to be common. Formation of hydrogen sulphide is apt to occur on a considerable scale, resulting in the precipitation

of ferrous monosulphide and the formation of sulphuric acid, the latter assisting in dissolving any calcium or other carbonates which may enter the environment of the black mud deposits. Carbonate fossils in such muds either disappear altogether or are replaced by iron sulphide. The hydrogen sulphide in the waters may affect neighboring areas, and dwarfed organisms result from its presence. Some lagoons, in whole or in part, particularly those associated with coral reefs, may have deposits consisting largely of calcium carbonate.

The stratification of lagoonal deposits should be regular and even, with little or no cross lamination due to currents, except near openings in the bar and about the mouths of inflowing streams. The shallowness of the water makes it possible for waves to leave their characteristic markings on the bottoms, so that every surface may contain ripple mark. Tracks, trails, "rain prints," and other markings may be common. The colors range from gray where the vegetable matter is scanty to dark and even black where it is abundant.

Lagoonal Deposits in the Geologic Column

Little seems to be known relating to lagoonal deposits in the geologic column. The Solenhofen lithographic stone has been interpreted as the lagoonal deposits of a coral reef, and a lagoonal origin has been suggested for the Birdseye limestone of New York. The shallow epicontinental Paleozoic and later seas should have been margined by many lagoons, and there should be deposits of this environment in every system. Few have been recognized, however, which probably indicates that some misinterpretations with relation to the stratigraphy exist.

THE ESTUARINE ENVIRONMENT AND ITS SEDIMENTS

An estuary is defined as that region in and adjacent to the mouth of a river in which the stream current is periodically barred from flowing into the sea by rise of tides, the water level in the stream being raised so that portions of the banks exposed at low tide are inundated at high. At high tide an under current of salt water flows upstream beneath fresh water. At low tide fresh water extends to a greater depth, and the salt water is partially replaced by fresh. An estuary to be important requires a considerable tidal range, with an enlargement of the river about its mouth due to coastal submergence. The environment passes upstream into the fluvial and seaward into the shallow neritic. The intervening area between the typical fluvial and typical neritic environment is the estuarine. Its limits are fluctuating. Its shore margins are like those of the littoral except for

the more or less decided variations in the salinity of the water. Important existing estuaries are the upper part of the Gulf of St. Lawrence, the upper part of the Bay of Fundy, Chesapeake and Delaware bays, and the estuaries of the La Plata, Thames, and Severn. Estuaries do not exist in tideless seas.

The salinity of different parts of an estuary has considerable range. Those into which there is a rather steady discharge of fresh water, as the St. Lawrence, have a somewhat constant salinity for any given place. Those in which the discharge of fresh water is subject to much variation may have considerable range in salinity for a given place. Variations in tidal range also have important effects. Some places have salt water over the bottom and fresh water above, and some parts of the bottom are alternately bathed by fresh and salt water. An estuary may have salt water flowing upstream at the same time that fresh water is flowing seaward on top.[157]

Due to the funnel-like shape of many estuaries, the tides tend to be high compared to the shores of the open sea. This leads to strong tidal currents, resulting in much scouring of the bottom.[158] The tides also restrict the areas of the estuaries through the building of marine and brackish-water marshes and mud flats. These features are well shown about parts of the Bay of Fundy.

Twice daily the tidal currents contend with the waters of the stream, following which the two work together to produce strong currents out of the estuary. Where the opposing currents conflict, there may be deposition of material held in suspension in either current, resulting in the formation of mud and sand banks on the bottom. In course of time these may become mud or sand flats or islands. This deposition leads to the concentration of the ebb and flow waters in the deeper channels, which are thus kept open. The tides may extend for long distances upstream, 600 miles in the Amazon, making the tidal bores. These concern only fresh water, and while a river to the extent of the influence of its bore is an estuary, the influence on the sediments is negligible except that current ripple mark and cross lamination may become reversed in direction.

The estuary of the Severn has been studied in detail.[159] Here the tidal currents flow at velocities of 6 to 12 miles per hour.

[157] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Ser. no. 107, Geol. Surv. Canada, 1921, pp. 17–18.

[158] Hunter, J. F., Erosion and sedimentation in Chesapeake around the mouth of Choptank River, Prof. Paper, 90-B, U. S. Geol. Surv., 1914.

[159] Sollas, W. J., The estuaries of the Severn and its tributaries; an inquiry into the nature and origin of their tidal sediment and alluvial flats, Quart. Jour. Geol. Soc. London, vol. 39, 1883, pp. 611–626.

> At high tide the tidal channel of the river is filled with a sea of turbid water, thick and opaque with tawny-coloured sediments; as the tide ebbs a broad expanse of shining mud flats is revealed fringing the coast; but so like is the water to the mud that, seen from a distance, it is hard to tell where the sea ends and the shore begins.

The mud appears to be partly derived from the rivers flowing into the estuary, partly from the erosion of the shores, and partly from the sea. This mud wanders back and forth, now carried inland by the tidal currents, now outward by the stream currents, withdrawals constantly being made for deposition in the sea, and accessions as constantly being made by the streams, and possibly by inflowing marine currents.

Due to variations in salinity, turbidity, and strong currents, the bottoms of those parts of estuaries subject to such variations do not have a large population of marine organisms. Estuarine faunas also may be composed of smaller individuals than the same forms in the open sea, as is illustrated by the fauna of the Baltic Sea, where such shells as *Mytilus* and *Mya* are not more than half as large as the same forms on shores of the Atlantic. The organisms of different parts of an estuary may be much unlike. Above the salt-water influence they are those of fresh water; seaward they are adapted to normal sea water. There should, therefore, be more or less mingling of marine and fresh-water organisms.

There is considerable range in the sediments of estuaries, and the units have somewhat lenticular deposition. Cross lamination and current ripple mark should show considerable variation in direction. The sediments on the bottom of the tidal portion of the Severn consist of

> a variable quantity of fine argillaceous granules, small angular fragments of colorless transparent quartz containing numerous minute included cavities, a few similar fragments of flint, siliceous fragments of a glauconitic green colour, minute crystals of quartz of the ordinary form, minute crystals of tourmaline, highly pleochroic and similar in form to the microscopic prisms of schorl, and minute rhombohedra of calcite.

The Severn muds contain siliceous and calcareous organic matter in the form of coccoliths and coccospheres similar to those in the adjacent Atlantic, the tests of several species of foraminifera, spicules of Alcyonaria, minute spines and fragments of echinoderms, spicules of calcareous and siliceous sponges, tests of diatoms, and shells of other invertebrates. The foraminiferal shells are generally empty, but a few were found filled with brownish material, and one was found practically replaced by pyrite. Above the limits of tidal action the muds appear to be of similar character, but the contained organic matter is of fresh-water origin.

A section of older deposits of the Severn estuary is as follows:

3. Upper clay which at the top through a thickness of 5 to 7 feet is more sandy than the 7 to 8 feet below. Below the clay are 1 to 2.5 feet of peat which is formed of aquatic plants at the base and has branches and other parts of trees on the top.
2. Lower clay with 1 to 4 feet of peat at the base.
1. Sand and mud underlain by gravel, the last resting on Triassic sandstone. The gravel contains pebbles and boulders of glacial origin.

Organic matter in the form of shells occurs in some of the layers,[160] and the thickness is about 50 feet.

Estuarine deposits are not likely to contain thick or extensive beds of carbonate sediments, though lenses of local extent may be not uncommon. The colors of estuarine deposits usually are gray or blue, and they may be black.

The general outline of an estuarine deposit should be rudely triangular, and it should grade outward into typical marine sediments and landward into those of fluvial origin. On the lateral margins there should be peats and dark muds or mud-cracked clays and silts.

There is no single criterion by which an estuarine deposit may be distinguished, but the aggregate of characters which have been stated and the general geologic relationships to fluvial and marine deposits may serve to differentiate them.

That estuarine deposits exist in the geologic column must be accepted as certain. Grabau has advanced the view that the black graptolite shales of the Utica type were deposited under estuarine conditions and the present writer is more or less in harmony with this view.[161] This carries with it the correlate that the graptolites are found in these shales not because the waters of deposition were the natural environments of life, but because they were the environments of death, and that, too, under conditions favorable for rapid burial and consequent preservation. The fluctuating and unstable conditions on the bottom repelled the benthos and hence the bottom muds after deposition did not make frequent passages through intestinal tracts with consequent disappearance of organic matter.

Marine Environments

The marine environments are those of the shallow water (neritic), the bottom intermediate to the deep sea (bathyal), and the deep sea (abyssal).

[160] Sollas, W. J., op. cit.

[161] Grabau, A. W., and O'Connell, M., Were the graptolite shales, as a rule, deep or shallow water deposits?, Bull. Geol. Soc. Am., vol. 28, 1917, pp. 959–964; Grabau, A. W., Origin, distribution, and mode of preservation of the graptolites, Mem. Inst. Geol., Nat. Res. Inst. China, no. 7, 1929, pp. 1–52.

To a considerable extent the littoral, delta, marginal lagoon, and estuarine sediments have marine characteristics. The sediments brought to marine environments are derived from all sources, but the greater portions are of terrigenous and pelagic origins.[162]

Bottom waters as a whole may be placed in four classes: (1) bottom waters carrying little mud or sand, and deposition of mud or sand on the bottom of slight quantity; (2) bottom waters very muddy, and deposition of mud large; (3) bottom waters carrying much sand, and bottom deposits composed of sand; (4) bottom waters more or less periodically carrying much sand or mud.

Under the conditions of clean waters over the bottom and small deposition of clastics, bottoms, other conditions being favorable, are likely to be densely populated, and such will also be the case in the waters above. There will also be an abundance of scavengers adapted to the food supply and the chances are that most of the organic materials will be broken and ground to pieces as a consequence of many passages through the digestive tracts of scavenger and bottom-eating organisms. The conditions for preservation of organic remains are poor, and rocks formed under these conditions are not likely to contain many well preserved shells.

The conditions of very muddy bottom waters and deposition of much mud are not congenial to many organisms, and the bottom population is small and of few species. The rapid deposition of mud, however, favors preservation of organic remains, and the fossil record may suggest a larger population than was the case. Contributions of organic matter may be made from outside, as the presence of muddy waters indicates presence of currents. These, however, are of low competency, and hence introduced organic matter would consist of small shells.

The conditions of bottom waters carrying much sand and bottom deposits composed of sand are also not favorable to many organisms, and such conditions seem usually to be accompanied by small bottom populations. The transportation of sand implies considerable competency, and there is likelihood of extensive introduction of shell materials from other bottoms. Here again a section of sediments formed under these conditions may suggest a greater abundance of life on the bottom than actually existed.

Bottoms irregularly or periodically subjected to the deposition of considerable mud, if the times of deposition are sufficiently far apart to permit

[162] Important works dealing with marine deposits are: Murray, J., and Renard, A. F., Deep sea deposits, in Challenger Repts.; Collet, L. W., Les dépôts marins; Murray, J., and Hjort, J., The depths of the ocean; and Andrée, K., Geologie des Meeresbodens, Leipzig, 1920. Reports of the different marine exploring expeditions should also be consulted.

colonization by organisms, offer the greatest possibilities for preservation of organic matter, as the influx of mud may bury and smother both the scavengers and predatory benthos and the organisms upon which they feed, producing a sedimentary deposit of calcareous shales and thin limestones abundantly filled with fossil shells.

It seems obvious that the marine deposits may not give a true picture of the abundance of marine life at the time of deposition. Differentiation needs to be made as to whether the organic remains in the sediments are of animals living where the remains are found, or whether the remains were transported from some other environment. Sediments, particularly limestones, with few fossil remains do not prove a small bottom population, as these sediments may represent a bottom that was abundantly populated and conclusion must be deferred until the rocks are examined in thin section to determine whether or not they are abundantly filled with fragments.

THE NERITIC OR MARINE SHALLOW-WATER ENVIRONMENT

The neritic environment of the sea is that portion of the bottom extending from the low-tide level to the depth of around 100 fathoms. It embraces the greater portion of the sea bottom known as the continental shelf, together with such epicontinental seas as Hudson Bay.

At the present time the neritic bottom of the sea is estimated to have an area between 10,000,000 and 15,000,000 square miles. About oceanic islands and some shores of the continents the neritic zone is narrow; about shores which have not been uplifted for a long time and those which have recently been submerged it may attain widths which in some cases exceed 100 miles. The distribution, extent, and depths of the most important areas of the neritic environment are shown in table 91.[163] Those parts of the continental shelf having depths exceeding 100 fathoms are arbitrarily assigned to the bathyal environment.

Were sea level to rise materially, the outer and deeper portions of the neritic zone would be added to the bathyal, but there would be an increase on the landward side through the overflooding of the lower lands of the continents. During those times of the geologic past when the lands were reduced to low peneplains, slight raises of sea level extended the neritic environment far into the hearts of the continents and added hundreds of thousands of square miles to its area. At times during the Cambrian, Ordovician, Silurian, Devonian, and Cretaceous the extent of sea bottom of neritic depths must have been fully twice as great as at present, and, if Walther's opinion that there was no deep sea until after the close of the

[163] Krümmel, O., Handbuch der Ozeanographie, Bd. 1, 1897, p. 113.

TABLE 91

LOCATION	AREA	DEPTH
	sq. km.	*meters*
Atlantic Ocean:		
America:		
Newfoundland shelf	345,000	150–200
Florida-Texas shelf	385,000	Mostly less than 50
Campeche shelf	170,000	Mostly less than 50
Guiana shelf	485,000	Mostly less than 50
South Brazil shelf	370,000	Mostly less than 50
Patagonian shelf	960,000	Mostly less than 50
Africa:		
Agulhas shelf	75,000	Mostly over 100
Europe:		
British shelf	1,050,000	Mostly under 100
Arctic Ocean:		
Norwegian shelf	93,000	200–300
Iceland-Faroe shelf	115,000	200–300
Barents shelf	830,000	200–300
North Siberian shelf (Nova Zembla to 155° W. long)	1,330,000	One-half under 50
Indian Ocean:		
Africa:		
Zambesi shelf	55,000	Mostly under 50
Asia:		
Bombay shelf	230,000	50–100
Burma shelf	290,000	Mostly under 100
Australia:		
N. W. Australia shelf	590,000	50–100
S. Australia shelf	320,000	50–100
Pacific Ocean:		
Australia:		
Tasmania shelf	160,000	50–100
Queensland shelf	190,000	Mostly under 100
Arafura shelf	930,000	50–100
Borneo-Java shelf	1,850,000	50–100
Asia:		
Tonkin-Hongkong shelf	435,000	Mostly under 100
Tunghai shelf (Strait of Formosa to Strait of Korea)	915,000	Mostly under 100
Okhotsk-Sakhalin shelf	715,000	50–100
Behring shelf	1,120,000	One-half under 50

Paleozoic be correct, the extent of the neritic environment during the Paleozoic may have been many times the present area.[164]

[164] Walther, J., The origin and peopling of the deep sea, Naturwiss. Wochenschr., 1904, transl. by LeVene, C. M., Am. Jour. Sci., vol. 31, 1911, pp. 55–64.

The seas between continents, as the Mediterranean, Caribbean, and Gulf of Mexico, which do not lie on the continental shelf, but are isolated parts of the deep sea, have been designated mediterraneans. These have neritic margins, but their bottoms descend to the depths of the bathyal and abyssal environments.

The neritic environment has different expressions depending upon whether it margins the shores of the open sea, an epicontinental sea, a coral island or barrier, a submerged bank, or a volcanic island.

The neritic environment on the shores of the open sea commonly has strong waves and currents to great depths. Tides and tidal currents are invariable. The faunas are normal and tend to have cosmopolitan characteristics and wide distribution. This is the typical neritic environment.

About coral islands and reefs there is great variety to the sediments and the faunas. In the lagoon of a coral atoll or the lagoon between a reef and the land the sediments commonly are extremely fine muds which may be almost wholly calcareous. Channels between the reefs may contain limestone gravel and sand. One fauna may dwell on the reef, another in the channels, a third in the lagoon, and a fourth in the deeper waters outward from the reef. The stratification ranges from none at all in the coral masses to the finest of laminations in the lime muds of the lagoons. The strata have inclinations ranging from essentially horizontal within the lagoons to an approximation to the angle of repose about the reefs. The neritic environment may embrace the whole of an epicontinental or epeiric sea. The waters may range from nearly fresh in such seas to high salinity. The tides may be much smaller than in the open sea or they may have a greater range. The Baltic Sea illustrates an epicontinental sea with brackish waters in its eastern areas, and its tides are small. Hudson Bay has strong tides. The faunas tend to be more or less provincial.

The neritic environment about volcanic islands is characterized by an abundance of volcanic matter in the sediments and the probable occurrence of high initial inclinations.

Processes of the Neritic Environment

PHYSICAL PROCESSES. Essentially the whole of the neritic environment is within the range of wave and current action, this being particularly true of the shoreward portions where the sediments may attain only temporary deposition. Near the shore the variations in wave and current trend are extremely great. Ripple and current mark have equally great variation in trend and development, and the strata commonly are cross-laminated to some extent. The shells which enter this portion of the neritic environment not infrequently are broken, and entire shells may have one or more healed

places. Due to the fact that the bottom of the neritic zone is subject to wave activity, it is near the critical point of deposition and erosion, and over large areas the sediments are only temporarily deposited. As a consequence, local unconformities or diastems are common. If sea level remains stationary sufficiently long, a base level of deposition may be reached, with cessation of deposition until a change of conditions produces a new base level above the original one. This must have occurred many times in the neritic environment of the geologic past, and there must be many stratigraphic breaks which are due to this cause. In nearly enclosed epicontinental seas the attainment of a base level of deposition is somewhat different from what it is in the open sea, as it is possible for an epicontinental sea to be filled up. A great volume of sediments may be deposited upon the landward margins of an epicontinental sea which later may be moved into the central deeper portions. This would give stratigraphic breaks about the margins.

Epicontinental seas may have weak tidal action and tidal currents. This condition leads to the presence of quiet bays and sounds of which the bottoms may become covered with black muds rich in hydrogen sulphide. This is illustrated by the limans of the east Baltic. Deep places in the bottom may contain similar muds. The shoreward waters of epicontinental seas with low tidal range may be so shallow as to destroy the effectiveness of waves for eroding at distances of many miles from the shore, and thus a vast stretch of shallow water may be given over to the deposition of muds and marine and fresh-water plant life with black muds as a result. It is thought that some black shales formed under such conditions. The waters of epicontinental seas may be abnormally salty or brackish, and dwarfed and provincial faunas are not unlikely. The shallowness of epicontinental seas may lead to the stirring up of previous deposits by storm waves. Lenticularity of units is the probable result.

It is to the neritic environment that streams bring the major portions of their waters with their burdens of suspended sediments, and it is upon neritic bottoms that great portions of these sediments come to rest. This deposition is permanent or temporary, depending upon the position of the bottom with respect to a base level of deposition. If the bottom is at or above this level, any deposits which are made will later be shifted outward to bathyal depths. The initial deposition is brought about by the checking of velocity and the electrolytes in solution in the sea water and the presence of colloids of opposite sign. If deposition is rapid, there is little differential settling.[165] Convection currents may form in the muds which settle rapidly, giving rise

[165] Johnston, W. A., Sedimentation of the Fraser River delta, Mem. 125, Geol. Ser. no. 107, Geol. Surv. Canada, 1921, p. 37.

to pit and mound structures. "Rain prints" formed by bubbles arising from the decay of organic matter are not improbable on the surfaces of the muds. Rates of deposition probably have an extremely high range, no doubt from a rate of a foot in a few days to the same thickness in many thousand years.

CHEMICAL PROCESSES. It is in the neritic environment where there is the greatest mingling of waters of different character, where there are immense quantities of decaying organic matter, where the waters are in rather general circulation from bottom to top, where there are great variations in temperature with consequent variations in carbon dioxide content, where there is much evaporation, where flourishes the greatest number of green plants, and where there is probably the densest population of marine invertebrates. As these conditions and processes are thought to be mainly responsible for the deposition of calcium carbonate, it follows that it is in the neritic environments that the greatest thickness of calcareous sediments has been deposited and deposition of calcareous sediments per unit area is now most rapid. The conditions quite generally are those of reduction.

ORGANIC PROCESSES. The neritic bottoms support a greater abundance of life than any other part of the ocean bottom of equal area. Bottoms which are sufficiently solid for long enough times to permit organisms to obtain and retain footholds are densely carpeted with both plants and animals, and the waters above such bottoms are equally abundantly filled with planktonic and nectonic life. It is on neritic bottoms that live the most mollusks, the most brachiopods, and other animals with thick and strong shells. Here also live the reef-building corals. Bottoms composed of gravel, sand, mud, and shells have each their own particular grouping of organisms, although many organisms thrive on several types of bottom. Black mud bottoms, because of limited quantity of oxygen and abundance of hydrogen sulphide, are not inhabited by a large variety of plants and animals. Bottoms composed of shifting sands also are scantily populated. There is possibility of sudden and vast destruction of life in neritic waters, such as the recent great destruction of the tile fish. Heavy rains in shallow waters may so change the salinity as to eliminate the bottom life almost totally. On the coast of Dorset, England, 1000 lobsters in boxes were killed in one night in 1863 by a heavy rain, and in 1865 on the same coast a sudden thaw in late January and early February produced so much melt water as to kill immense numbers of *Octopus vulgaris*;[166] similar great destruction of fish and other marine animals off the coast of India at the time of the abundant rainfall of the southwest monsoon has been described by Denison.[167]

[166] Geol. Mag., vol. 2, 1865, pp. 141–142.
[167] Denison, W., On the death of fishes during the monsoon off the coast of India, Quart. Jour. Geol. Soc., vol. 18, 1862, p. 453.

A great storm in 1918 over the Great Barrier Reef of Australia caused so much water to fall that all animals were killed locally to a depth of 10 feet below mean tide level.[168]

Stratification of Deposits in the Neritic Environment

Deposits adjacent to the shores are usually lenticular, with much cross lamination and great range in dimensions or particles. This is particularly true with respect to the deposits about coral reefs and in the separating channels and on shoreward bottoms with steep slopes. Bottoms with steep slopes have sediments deposited with high initial inclinations, and slumping should be not uncommon. In deeper waters the units are better defined, and there is less irregularity. The experiments of Kindle[169] suggest that laminations in marine sediments are sharply defined.

Distribution of Sediments on Neritic Bottoms

In general, the coarser sediments are adjacent to the shore and grade into finer deposits seaward, but the exceptions to this generalization are many. Bottoms adjacent to low shores without streams are apt to receive fine sediments, although some bottoms near such shores may have currents sufficiently strong to bring coarse sediments. On many existing bottoms muds and calcareous sediments are being deposited as far up the beach as the waters reach. Bottoms adjacent to high shores undergoing erosion commonly receive much coarse material derived from rocks of the shore. In greater depths of neritic waters the sediments tend to be more uniform in character and to consist very largely of calcareous matter and mud. About coral reefs, as shown in the ancient reefs of Gotland, Anticosti, and elsewhere in the Silurian and other systems, the distribution of sediments is extremely irregular. Any bottom of sufficient depth to permit strong waves and not so deep but that waves and currents reach bottom with sufficient competency to move sands and muds, should show considerable variation in its sediments and correspondingly in its faunas. Such vertical variations in sediments as are exhibited in the Ordovician about the Cincinnati Arch, in the Ordovician and Silurian of the Anticosti region, and in the Pennsylvanian of the Mid-Continent region imply variations of equal extent in the lateral, and variations as great should be expected in the faunas.

Sediments of the Neritic Environment and Their Colors

The sediments of the neritic environment are mainly terrigenous and pelagic. Cosmic and volcanic materials are present, the former constituting

[168] Yonge, C. M., A year on the Great Barrier Reef, 1930, pp. 79–80.
[169] Kindle, E. M., Diagnostic characteristics of marine clastics, Bull. Geol. Soc. Am., vol. 28, 1917, p. 908.

only a very small and inconspicuous part of the whole and the latter being only locally important.

The terrigenous sediments consist of gravels, sands, and muds. The gravels and sands tend to be well sorted; most are long travelled; and quartz is the most common substance. Excellent rounding seems to be the rule in the larger dimensions. The small particles are angular. The muds have gray, blue, green, red, and black colors. The red muds occur about the mouths of some tropical rivers like the Amazon. The black muds have limited distribution and are confined both to deep and shallow bottoms with poor circulation. The blue, gray, and green muds are found at all depths. The green color appears to be due to glauconite, which in the earlier geologic periods was abundantly developed over shallow portions of the neritic environment, but at the present time it does not appear to be so common in shallow waters.

The pelagic sediments consist of shell, coral and algal materials, and matter precipitated from solution. Most consists of calcareous matter, but some silica, iron carbonate, and iron oxide are deposited in this environment, and it is probable that the extent of such deposition has been greater in past ages than at present, as the Lake Superior and some of the other silica and iron sediments seem to have been deposited in waters of depths not greater than those of the neritic environment, although it is not known that the waters were salty or the sediments pelagic. A magmatic source has been postulated in some cases for the iron and silica. Before the pelagic foraminifera became of importance in the precipitation of calcium carbonate and thus increased its deposition on the deeper bottoms, it is suggested that there was an extremely great concentration of this sediment in the neritic environment. Foraminifera do not seem to have become abundant prior to the late Mesozoic or Tertiary, since which time there has been large and abundant deposition of lime over deep bottoms. Deposits of carbonaceous matter of pelagic origin are occasionally made, but the quantity is small and of local distribution. It seems improbable that peat deposits could originate in this environment.

The Marine Cycle

The marine cycle affects littoral, estuarine, neritic, and locally other sediments. In the early stages of the cycle the shores are irregular; they may be high; and the bottoms may descend rather abruptly from the shore (exceptions are where low, flat lands have been submerged). Under these conditions the sediments supplied are apt to be in quantities larger than can be disposed of by the marine waves and currents. The bottom is then built up, and the building continues until the sea's ability to dispose of material

is adequate for the quantity contributed. The shore by that time will have acquired less irregular outlines—the headlands having been more or less cut away and the indentations filled. As the cycle continues, the quantity of sediments contributed gradually grows less, and any energy of the marine agents of transportation in excess of that necessary for disposing of the sediments contributed will be utilized to remove part of that previously deposited. Ultimately the old age of the cycle is attained, by which time the shore is far inland from its place of beginning, and an eroded surface has been cut across the neritic deposits of the earlier portion of the cycle and also across any lagoonal, estuarine, littoral, and other deposits which may have been present. Further progress carries this erosion surface to greater depths, the rate of erosion becoming progressively slower as the base level of erosion or wave base (about 600 feet below sea level) is approached.[170] The sediments removed in this erosion are moved outward into deeper waters (fig. 3).

Criteria for the Determination of Neritic Deposits

Neritic deposits may be composed of gravels, sands, muds, calcareous matter, glauconite, flint and chert, various minerals of iron, and rarer substances. An abundance of shells may or may not be present, depending upon the facies of the environment, the rates of deposition, and the abundance of scavenger organisms. Occasional layers contain shells and tests in excellent preservation. Usually they are more or less broken. Trails of marine animals and marks made by floating objects may occur, and ripple and current marks are generally common. There is a somewhat sharp delimitation of laminations and strata, and the continuity of bedding seems to increase with depth and distance from shore. These are positive characteristics. Negative characteristics are the absence of mud cracks and the tracks of land animals. The occurrence of thick conglomerates suggests a continental origin. The thickness of neritic sediments is limited only by the distance of the bottoms to a base level of deposition plus the distance of rise of sea level.

Neritic Deposits of the Past

It seems probable that the marine sediments of the known geologic column were almost wholly deposited in the neritic environment. A few may have originated in the shallower depths of the bathyal environment. The estimated average thickness of sediments on the continents is placed at one mile for the 45,000,000 square miles which are underlain by sedimentary rocks. The estimate probably is high. This gives 45,000,000 cubic miles of sedi-

[170] Johnson, D. W., Shore processes and shoreline development, 1919.

mentary materials on the continental areas. Probably 80 per cent, or 36,000,000 cubic miles, is of neritic origin, most of the rest being of continental origin or mixed continental and marine. Neritic sediments over the existing neritic environment are estimated to have an average thickness of 3 miles, giving an additional volume of 30,000,000 cubic miles.

THE BATHYAL ENVIRONMENT AND ITS SEDIMENTS

The bathyal environment of the sea bottom is that portion between depths of 100 and 1000 fathoms. Its shallower depths receive more or less light, and some plant life is present. The area is around 15,000,000 square miles, some of which is upon the deeper parts of the continental shelf and the rest upon the continental slopes. The sediments by slow transitions grade on the seaward side into those of the abyssal depths and by equally slow transitions on the landward side into those of the neritic bottoms.

Processes of the Bathyal Environment

PHYSICAL PROCESSES. Only the occasionally strong waves and currents are thought to make any impression on the bottoms, so that wave and current markings should be of limited occurrence. Sediments once deposited are thus rarely removed. Deposition takes place through settling from suspension, through a slow drift over the bottom from the neritic district, and through slumping. About many oceanic islands and the younger continental margins are steep slopes down which materials are readily moved to the deeper waters of the bathyal environment. Such steep slopes lead to inclined deposition and favor slumping, particularly if the steep slopes are the loci of seismic movement. The rate of deposition is thought to be slow, and not subject to serious interruptions.

CHEMICAL PROCESSES. The same processes noted in connection with the neritic environment are operative in the waters and sediments of the bathyal, but probably with less intensity for most of them. As sediments are precipitated from solution, they must sink a considerable distance before reaching bottom, and there is thus opportunity for return to solution. The conditions seem almost entirely to be those of reduction.

Some of the epicontinental seas of great depths are connected with the main body by shallow passages of neritic depths. This is the case in the Black Sea. Such conditions may lead to poor circulation and the development over the deep bottom of mud rich in hydrogen sulphide and the dark monosulphide and disulphide of iron. Such waters may be unfit for life. The muds are dark when wet, but the dark color tends to disappear on drying unless there is sufficient organic matter present for its maintenance.

ORGANIC PROCESSES. Bathyal bottoms are covered with numerous

marine organisms where conditions permit. As light adequate for green plant growth does not penetrate to any great extent in bathyal depths, green plant material is absent unless brought in from shallower waters, and animal life is limited in accordance. In general, life seems to be prolific on bathyal bottoms, but there probably is not the abundance characteristic of neritic bottoms. Scavenger action is probably as intense as on shallow bottoms.

Structures and Continuity of Strata in Bathyal Deposits

The strata should be continuous over large areas. The exceptions are on the steep slopes about oceanic and coral islands and along the younger margins of the continents. Under such conditions nearness to the distributive areas may develop lenticularity of units, but these should be on a larger scale than occurs in neritic waters. The strata have an initial inclination determined by the surface and rapidity of deposition. This probably is gentle in most instances. Where it is sufficiently steep, slumping may take place. The sediments may be cross-laminated in the shallower portions of the environment, and both types of aqueous ripple marks may be present, but each probably is not common.

Sediments of the Bathyal Environment

The sediments of the bathyal environment are red, green, gray, and black muds, glauconite, calcareous materials, volcanic muds and sands, and rarer substances. Sands of terrigenous origin may also be present. The calcareous sediments consist of coral muds and sands, various oozes, and shell matter. According to the "Challenger" report, the coral muds and sands cover an area of 2,236,800 square miles, with the former having a mean depth of 740 fathoms and extending to a depth of 1820 fathoms, and the latter a mean depth of 176 fathoms. The volcanic muds and sands cover an area of 600,000 square miles, with the muds having a mean depth of 1033 fathoms and a range from 260 to 2800 fathoms, and the sands a mean depth of 243 fathoms and a range from 100 to 420 fathoms. The green muds and sands cover an area of 850,000 square miles, with the former having an average depth of 513 fathoms and a range from 100 to 1270 fathoms, and the latter an average depth of 449 fathoms with none collected from depths greater than 900 fathoms. The red muds cover an area of 400,000 square miles, with an average depth of 623 fathoms and a range from 120 to 1200 fathoms. The blue muds extend over 14,500,000 square miles at an average depth of 1421 fathoms and a range from 125 to 2800 fathoms.[171]

[171] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891.

Bathyal Deposits in the Geologic Column

It is not certain that sediments deposited in the bathyal environment are present in the exposed geologic column, but it is not unlikely that some parts of the shallower parts of this environment have been elevated above sea level. It seems probable that the total quantity of sediments deposited in the bathyal environment is extremely great, as sediments once deposited are permanent and do not experience the frequent erosion which is the common fate of neritic sediments. The volume, of course, is unknown, but it is thought probable that 40,000,000 to 50,000,000 or more cubic miles of sediments must lie beneath bathyal bottoms.

THE DEEP-SEA ENVIRONMENT

In the deep abyss of the ocean there is no light other than that emitted by the phosphorescent organs of some of the animals living there. The pressure is tremendous, rising with depth at the rate of a little over a ton per square inch per mile, so that at a depth of 4 to 6 miles the weight on each square inch is 5 to 7 tons. The temperature is around 40° F. at all times. Currents and waves in the ordinary sense do not exist, and there is no appreciable motion of the water except in narrow channels and at times of earthquakes.

In the deep-sea environment may be included all that portion of the sea bottom which lies below the depth of about 1,000 fathoms. This gives an area of about 115,000,000 square miles. The shallower portions of the environment have deposits which are like those of the bathyal.

The absence of light eliminates green plants and any plants requiring light. Animals requiring green plants for food are thus not likely to be present. The darkness makes eyes unnecessary or leads to their development to an immense size in order to catch the feeble gleams emitted by animals with phosphorescent organs. The generally unfavorable conditions are responsible for the much smaller variety of organisms in the deep sea and for fewer individuals than exist in shallower waters.

The absence of currents and the little density of population coupled with the great pressure have made supporting and protecting structures more or less unnecessary in organisms, and such are very thin and fragile.

The sediments which reach the deep abyss are of cosmic, volcanic, terrigenous, and pelagic origin. The cosmic particles are not important from the quantitative point of view. They probably fall in approximately equal quantities over the entire surface of the earth, but because of the slowness of deposition over the bottom of the deep sea they have a greater relative importance there than in any other environment. The sediments of vol-

canic origin consist of volcanic ash and pumice. In many instances these are little decayed, but more frequently the pumice is considerably altered and its soluble parts removed; also in many instances the pumice is deeply impregnated with manganese oxide. The sediments of terrigenous origin have been carried by wind, water, or ice. The particles carried by ice may be of large size, and their occurrence in deep-sea sediments introduces components which are abnormal to the environment. Similar large particles may be floated to the deep sea in the roots of trees or the holdfasts of marine plants. According to Murray and Hjort, these fragments should settle into the muds of the bottom with the longer axes in vertical position,[172] but it is by no means certain that the assumption of this position is the rule. The sediments carried by wind and water are very fine and settle with extreme slowness, and by the time they have reached the bottom all matter soluble in the sea water or alterable to a soluble state has been dissolved, so that little remains other than ferric oxide and aluminum silicate. The general assumption is that the quantity of terrigenous sediments in the deep abyss is not large, but it does not seem that this assumption is warranted. The writer has presented evidence suggesting that the total volume of inorganic sediments over the deep abyss is of the order of magnitude of 80,000,000 cubic miles, or nearly twice the volume of all the sediments on the land.[173] Parts of this are of volcanic origin, but it seems probable that the major portions are of terrigenous derivation. The pelagic sediments consist of the hard parts of organisms which lived in the upper lighted waters, or on the bottom. The contributions from the latter source appear to be slight, as the population is small, and the shells are thin and fragile. In the shallower portions of the deep sea the contributions from the lighted waters are extremely important. As the shells from the lighted waters sink, those most fragile and delicate are dissolved, and only the very resistant, compact, and large reach the bottom, in whose deposits their relative importance is great because of the small quantities of other constituents. Those which reach the bottom are corroded by solution to some degree, but none shows abrasion and fracturing from wave and current action. Some may have been crushed by predaceous animals. The actual importance is also extremely great, and it is estimated that the total quantity approximates 40,000,000 to 60,000,000 cubic miles.

Deep-sea deposits thus consist largely of the insoluble residue of materials which have settled through many feet of water, volcanic and cosmic matter, and the shells of pelagic organisms, the last decreasing in importance with

[172] Murray, J., and Hjort, J., Depths of the ocean, 1912, p. 207.
[173] Twenhofel, W. H., Magnitude of the sediments beneath the deep sea, Bull. Geol. Soc. Am., vol. 40, 1929, pp. 385–402.

depth. The samples collected by the "Challenger" Expedition show a progressive decrease of calcium carbonate in the sediments with depth. This is shown in the table which follows:[174]

	Per cent
Samples under 500 fathoms average $CaCO_3$	86.04
Samples between 500 and 1000 fathoms average $CaCO_3$	66.86
Samples between 1000 and 1500 fathoms average $CaCO_3$	70.87
Samples between 1500 and 2000 fathoms average $CaCO_3$	69.55
Samples between 2000 and 2500 fathoms average $CaCO_3$	46.73
Samples between 2500 and 3000 fathoms average $CaCO_3$	17.36
Samples between 3000 and 3500 fathoms average $CaCO_3$	0.88
Samples between 3500 and 4000 fathoms average $CaCO_3$	0.00
Samples over 4000 fathoms average $CaCO_3$	trace

This progressive decrease in calcium carbonate with depth may be largely assigned to the high carbon dioxide content of the deep waters, but the small production of shell matter on the bottom and the great depth through which shells from the lighted waters must sink are also responsible. The writer has suggested that earlier deep-sea sediments may not have had as high a content of lime carbonate as those of the present, and that this sediment did not become important in deep-sea deposits until the abundant development of pelagic foraminifera toward the end of Mesozoic time. Since the advent of these organisms there has been a continuous withdrawal of lime from sedimentary circulation, and it is possible that future ages may see a poverty of this salt due to its permanent burial beneath the deep sea.

The deposits of the deep sea contain many secondary products of which crystals of phillipsite and nodules of phosphate and manganese are the most abundant. The manganese nodules are confined mostly to the red clays, but also occur in the globigerina oozes. The occurrence of the resistant parts of upper-water animals is also a distinctive feature of the deposits of deep waters. A single dredge made by the "Challenger" in the central Pacific from a bottom of dark chocolate clay at a depth of 2385 fathoms yielded between 2 and 3 bushels of manganese nodules of which the diameters were between 1 and 2.5 mm. In addition there were over 1500 specimens of shark teeth and fragments, about 50 ear bones of whales, 12 rounded pieces of pumice of which the largest was about the size of a hen's egg, and 6 rounded pebbles or cobbles of which one of basaltic rock was over 3 inches in diameter; others were of gneiss and granite. The rock fragments probably were ice borne.[175]

The rate of deposition of deep-sea sediments must be extremely slow, as attested by the abundance of shark teeth and other uncommon substances.

[174] Murray, J., and Renard, A. F., Deep sea deposits, Challenger Rept., 1891, p. 279.
[175] Murray, J., and Renard, A. F., op. cit., pp. 359–360.

A minimum rate of one foot in 87,100 years has been suggested.[176] Except in volcanic regions and regions of recent faulting, the strata must be deposited on nearly level surfaces, with each layer extending in essentially uniform character for immense distances.

Summary of Characteristics of Deep-sea Sediments[177]

(1) Deep-sea sediments usually contain no large fragments of quartz or other continental rocks except as such may be dropped by floating ice or plants. Exceptions are where deep sea is close to land. (2) They contain no plant residues which are brown or black in color. (3) They are piled in horizontal layers and are spread over marvelous distances. (4) They contain no or few remains of shallow-water animals or plant eaters. (5) By very slow and gradual transitions they are connected with the shallower water sediments of another origin. (6) There are no features due to wave and current action. (7) The deepest deposits contain an abundance of the resistant parts of swimming organisms and many things which are not common in other environments. (8) The shell matter either is more or less corroded by solution or is fragile and thin, the former having settled from above, the latter being derived from organisms living in the environment.

These characters are not always present. An earthquake wave may move the waters to the greatest depths and thus produce current marks in the deepest deposits.

The Sediments of the Deep Sea

The sediments of the deep sea consist of red clay covering 51,500,000 square miles on bottoms ranging in depth from 2225 fathoms to the deepest known, and having an estimated volume of 75,000,000 cubic miles; globigerina ooze covering 49,520,000 square miles at a mean depth of about 2000 fathoms, but occurring as deep as 2925 fathoms and as shallow as 400 fathoms, and having a volume estimated to range from 50,000,000 to 100,000,000 cubic miles; diatom ooze covering 10,880,000 square miles with a mean depth of 1477 fathoms, but present in depths of 600 to 1975 fathoms, and with an estimated volume of 3,900,000 cubic miles; radiolarian ooze extending over 2,290,000 square miles with a mean depth of 2894 fathoms, found in depths from 2350 to 4475 fathoms, and estimated to have a volume of 19,900,000 cubic miles,[178] and pteropod ooze over 400,000 square miles at an average depth of 1044 fathoms.[179]

[176] Twenhofel, W. H., op. cit.

[177] Walther, J., The origin and peopling of the deep sea, Naturwissen. Wochenschr., 1904, Transl. by LeVene, C. M., Am. Jour. Sci., vol. 31, 1911, pp. 55–64.

[178] The figures of volume are taken from Twenhofel, W. H., op. cit.

[179] Murray, J., and Renard, A. F., op. cit., p. 248.

Deep-sea Sediments in the Geologic Column

Walther[180] expressed the opinion that no deep sea existed until the Mesozoic, as the expression of the present deep-sea faunas is Mesozoic, and Paleozoic elements are lacking. If this opinion is correct, no Paleozoic deep-sea deposits ever existed. At any rate, none has been identified. Clarke and others have referred certain black shales to a deep-sea origin under conditions similar to those of the Black Sea, but these shales are best interpreted as having originated in other environments.[181] Formerly the Cretaceous Chalk was referred to a deep-sea environment, but this view has very generally been abandoned. Grabau has suggested that some of the massive limestones of the eastern Alps and some of the Alpine Jurassic beds may be of comparatively deep-sea origin, as some of them contain few or no organic remains other than the opercula of ammonites.[182] Malta, Barbados, and Christmas Island in the East Indies are said to possess true deep-sea oozes of Tertiary age, the occurrences being assigned to local upheavals from the bottom of the deep sea.[183] Mesozoic deposits which appear to have developed in the deep-sea environment have been described by Molengraaff and Brouwer from the islands of Borneo, Timor, and Rotti of the East Indies. The deposits have been designated the Danau formation and cover some 40,000 sq. km.; the age is pre-Cretaceous and perhaps Jurassic. The sediments are said to contain no constituents suggestive of terrigenous sources. Manganese is common, occurring as grains in red shales; nodules in red shales, hornstone, and chert; and slabs in siliceous clay shales and radiolarian cherts. The strata consist of radiolarian hornstone or flint, which is composed of closely packed tests of radiolaria, and bright red argillaceous chert or siliceous clay shale. The latter differs from the radiolarian chert in containing fewer radiolaria, more iron and clay, and less silica. The two types, however, gradually pass into each other. The radiolarian chert is interpreted as indurated radiolarian ooze and the siliceous red clay shale as indurated red clay. The facts suggest that the Danau formation represents a true deep-sea deposit, and, if so, it is the most important occurrence known.[184]

180 Walther, J., op. cit.

181 Clarke, J. M., The Naples fauna, Mem. 6, New York State Mus., pt. ii, 1904, pp. 199–254.

182 Grabau, A. W., Principles of stratigraphy, 1913, p. 678.

183 Walther, J., op. cit., p. 60; Schuchert, C., Science, vol. 69, 1929, p. 142.

184 Molengraaff, G. A. F., On the oceanic deep-sea deposits of central Borneo; Kon. Akad. van Wetens. Amsterdam, Sec. of Sciences, vol. 12, 1909–1910, pp. 141–147; On the occurrence of manganese nodules in Mesozoic deep sea deposits from Borneo, Timor, and Rotti; their significance and mode of formation, Ibid., vol. 18, pt. i, 1916, pp. 415–430,

CHAPTER VIII

FIELD AND LABORATORY STUDIES OF SEDIMENTS

The study of sediments is concerned with the solution of five problems: what the sediments are and their characteristics, the changes occurring between their deposition and lithification, the environments in which they were deposited, the processes responsible for their transportation and deposition, and the sources from which they were derived. The economic products derived from sediments are by-products of the study. In some cases the solution of all of these problems may be attained, but in the present state of investigation and knowledge results are more or less incomplete, as geologists have not yet acquired the ability to recognize and evaluate all characters of sediments and to appreciate their importance and relations. Studies are made both in the field and laboratory, the former yielding the broader information and a certain amount of detail, the latter giving exact information with respect to detail.

Field Studies of Sediments

Field studies of sediments should yield an adequate description of the dimensions of the rock units, their colors, their larger sedimentary structures, their megascopic composition in organic and inorganic constituents, and the broader relations of the sedimentary units, and should suggest the provenance and distributive areas of the detritals of the sediments. In the study of a rock section the largest units recognized should be described first and then in order to the smallest. Measurements are best expressed in the metric system and should be sufficiently precise, but ordinarily absolute accuracy is not essential. Statements should be definite and not ambiguous, and when doubt exists as to the meanings of terms used, they should be defined. It is better that descriptions be profuse than scanty. Photographs and diagrams should be made wherever possible.

So far as possible, hypotheses relating to the problems of sedimentation should be thoroughly tested in the field, and the problems should be studied in accordance with the "method of multiple working hypotheses."[1] Many hypotheses suggest many lines of attack and lead to keener and more exact study and observation than might otherwise be made. Every sedimentary

[1] Chamberlin, T. C., The method of multiple working hypotheses, Jour. Geol., vol. 5, 1897, pp. 837–848.

rock contains an immense quantity of data, and it is virtually impossible to state in advance which facts are the most important and which will lead most directly to the solution of the problems. The history of science has too often demonstrated that characters considered trivial were of the greatest importance in that they and their relations contained the clue to a particular problem. One needs but to recall former disregard of cross lamination, ripple mark, positions of fossil shells, flow and fracture cleavage, drag folds, etc., by geologists who were attempting the unraveling of the structure and stratigraphy of formations containing these structures. It is, therefore, vital that every character within one's knowledge, so far as each relates to the problem of interest, should receive careful observation and study. The relations of the characters to each other are of equal, if not of greater importance than the characters themselves, and their larger aspects are seen to best advantage in the field.

Geologists, in general, and sedimentationists, in particular, should follow a precept taught by the late Professors John Duer Irving and Joseph Barrell, which holds that "a geologist working in any region should go on the assumption that he is never to see the region again and that it is up to him to get all the information available." The precept, of course, is an ideal, as points of view developed after a visit will show that information might have been obtained had this point of view been realized when the rocks of the region were seen. Most geologists will recall having failed to observe certain characters of sedimentary or other rocks due to oversight, and in order to avoid this failure experience has demonstrated that it is wise to carry a schedule for field observation and description. The schedule which follows is slightly modified from one organized through the Committee on Sedimentation of the National Research Council.[2]

SCHEDULE FOR FIELD DESCRIPTIONS

A. 1. External form of rock unit. Lenticular, persistent, regularity in thickness, etc.; dimensions.

2. Relations to other rock units; conformable, unconformable. Type of unconformity, origin, and environment of origin of the dividing surface. Relief of an unconformity, nature of lower surface, character and sequence of materials in basal and immediately succeeding units of overlying formation.

B. Color. Color of the unit as a whole; rock wet or dry, in shade or sunlight. This should follow Goldman and Merwin's or some other recog-

[2] Modified after Goldman, M. I., and Hewett, D. F., Schedule for field description of sedimentary rocks, Nat. Research Council, published by the U. S. Geol. Surv. See also Tieje, A. J., Suggestions as to the description and naming of sedimentary rocks, Jour. Geol., vol. 29, 1921, pp. 650–666.

nized color chart and not be left to impressions which are apt to vary from day to day.

C. Sedimentary structures.

1. Bedding.

a. How manifested: sharp; by shale or other partings; by difference in texture, color, etc.; transitional, shaly, banded, without parting.

b. Shape of bedding surfaces: even, undulating, ripple-marked, wave- and current-marked, etc.; irregular. If bedding surfaces are not even, give details of form and dimensions of features. Presence of stylolites should be noted.

c. Cross lamination: inclinations and directions of inclinations of foresets; nature of bounding planes of cross-laminated units; position of truncation of the cross laminations.

d. Thickness of beds: comparative thicknesses. Relations of thickness; random, rhythmic. If thickness is variable, relation between thickness and composition, bedding, etc. Factors responsible for the conditions.

e. Attitude and direction of bedding surfaces: horizontal, inclined, curved. Relation to each other: parallel, intersecting, extent; angles between different attitudes and directions; dips, strikes; relations of size, composition, shape, etc., to attitude and direction; relation of composition to different types of bedding. Are the attitudes primary or secondary?

f. Markings on bedding surfaces: mud cracks, ripple marks, rain prints, bubble impressions, ice crystal impressions, trails, footprints, etc. Details and dimensions of each feature.

g. Contemporaneous deformation: indicated by edgewise or other conglomerates, folding or crumpling of individual beds, etc. Is the deformation due to settling, gliding, or other causes? If due to gliding, the causes for such taking place and the place of origin of the materials.

2. Concretions.

a. Form, size, color, composition, variations in each respect.

b. Internal structure: nucleus organic or inorganic; center hollow; homogeneous; banded horizontally, concentrically, etc.; radial; compact; vesicular.

c. Boundary against country rock: sharp, transitional.

d. Relation of bedding to concretions: continuous through concretions or ending abruptly against them; deflected above, below, both; thinned above, below, etc.

e. Distribution: random; regular; if regular, intervals between groups (layers); differences between characters of concretions in different groups (layers). Relation of distribution to other characters, as composition,

jointing, fissuring, folding, etc., of country rock; topography; surface; ground-water level; etc.

f. Fossils in concretions: random, surface, in bands, etc.

g. Relation of composition of concretions to containing rock.

h. Other structures: stylolites, cone-in-cone, septaria, etc.

D. Composition.

1. Inorganic constituents.

a. Mineralogy or lithology of principal constituents. Rare constituents. Parts authigenic and allothogenic or detrital.

b. Size: prevailing size if fairly uniform; range in sizes if not; proportions of different sizes as determined by preliminary sieving where feasible; distribution of sizes with relation to other features; vertical and lateral variations in sizes.

c. Shape: crystalline (automorphic), angular, subangular, subrounded, rounded; relation of shape to size, material, position in beds, etc. For quantitative results on pebbles, etc., estimate or measure radius of curvature of sharpest edge, radius of curvature in the most convex direction on the flattest portion of the surface, mean radius, and maximum and minimum diameters.[3]

d. Character of surface of particles: glossy, smooth, mat (ground glass surface), pitted, chatter-marked, etc.

e. Orientation: if not equidimensional, direction of different dimensions with respect to bedding, to each other, etc.

f. Chemical and internal physical condition: fresh, decomposed, cracked, etc. Age relations of these features.

g. Packing: closeness and manner.

h. Pore space.

i. Cement: present or absent; proportion; composition; variations in composition vertically and laterally and in relation to other characters; disposition with respect to bedding, fracturing, fossils, etc.

2. Organic constituents.

a. Kinds and proportions to each other and the inorganic constituents of the rock.

b. Size: does the distribution of sizes show mechanical deposition?

c. Condition: entire, fragmental, partly dissolved, healed shells, etc. Relations to kinds.

d. Distribution: with respect to character of beds, kind of organisms,

[3] Wentworth, C. K., Method of measuring and plotting the shapes of pebbles, Abstract, Bull. Geol. Soc. Am., vol. 32, 1921, p. 89; Bull. 730, U. S. Geol. Surv., 1922, pp. 91–102; A field study of the shapes of river pebbles, Ibid., pp. 103–114.

bedding, evidence of burrowing, etc. Have the shells been transported, or are they in the places where their builders lived?

e. Orientation: with respect to bedding; with respect to life habits. Possible manner of death, etc.

f. Positions of the shells: concave upward, downward.

COLLECTION AND PRESERVATION OF SAMPLES

The field study of sedimentary rocks is usually not adequate to acquire all the desired information, and laboratory studies are necessary for attainments of certain lines of information, to supplement the field observations, and to test further explanations entertained in the field.

Specimens may be collected:

(a) To form part of a complete series representing every bed or what appears to the collector to be a distinct type of rock.

(b) To represent some peculiar type of rock which the collector cannot sufficiently identify in the field, or which he recognizes to be new.

(c) To help in the testing of hypotheses formed in the field as to the origin of the characters of any rock.[4]

As a general proposition, it is usually best to collect a complete series of rocks. Such is the method of students of igneous and metamorphic rocks, and sedimentationists may do well to follow their method. It needs to be emphasized that in the collection of material for laboratory study the solutions of the problems are not attained through collection of specimens at random or collection of peculiar and curious specimens; the problems may be solved, rather, through study of complete suites of specimens from the terrane that is being investigated.

The collection of material from sedimentary deposits is governed by the same general rules and should receive the same care as the collection of samples of ores and other products of nature which are taken for commercial purposes. It is important that the material representing a given horizon should be taken from points widely enough distributed to give the various phases of the deposit. Beds of a generally uniform character may be "sampled." Samples from consolidated deposits should be unweathered. Samples may be acquired from surface exposures; they may be cuttings of rotary or cable drilling; or the more or less complete core of diamond drilling.

All samples should be guarded against contamination through entrance of foreign materials, should be adequately labelled as to locality, horizon, and facies of collection, and the complete history of collection should be given together with reasons for collecting. The object is to have all necessary in-

[4] Goldman and Hewett, op. cit.

formation accompany the sample or specimen. Samples and specimens derived from unknown localities and horizons usually are valueless. To avoid the transportation of unduly large quantities, the first stage of "sampling down" should be carried out in the field so far as conditions permit, but it is much better to ship large quantities to the laboratory than to attempt imperfect sampling where facilities are inadequate for performing such work properly. The actual "sampling down" is accomplished by the well known "quartering" method or by the aid of one of the various devices now on the market. Muds and other finely divided sediments which it is inadvisable to dry for fear of change in the colloidal constitution or chemical change should have sufficient water added so that the mixture will easily flow, following which the sample may be reduced with a "cross grid" sampler.

One of the first and most important lessons a student of sediments should learn is that like materials tend to become segregated, and in splitting samples to reduce the material to be transported one must be constantly on guard to see that the part of a sample intended for study is representative.[5]

Collection of samples from unconsolidated materials is done either upon the surface or beneath a water cover. The former may be done with the hands or some form of small shovel or scoop. Care should be taken to see that the materials collected adequately represent the deposit from which they are taken. Collection of materials from beneath a water cover of such shallow depth as to be accessible to the hands involves nothing greatly different from surface sampling. Materials collected from depths not so accessible involve some form of mechanical instrument, several of which have been devised. Some merely sample the materials on or near the surface, whereas others obtain a core of the bottom to depths of several feet. As bottom samplers and sounders are more or less constantly being perfected, it does not seem worth while to attempt description of any, and the reader should refer to works appropriate to the subject or to the institutions interested in oceanography or limnology.

Most bottom sediments contain organic matter of animal and vegetable origin, and if a preservative is not used, decomposition is soon initiated and the organic components changed or dissipated, and concomitantly the decomposition and the resulting products may alter the character of the inorganic constituents. Grain alcohol is very satisfactory for preservation of the physical form of animal life or for samples intended for mechanical study only, but this preservative is rarely satisfactory for determination of the chemical character of the organic matter. The U. S. Bureau of Fisheries used a 2 per cent solution of sodium hydroxide to preserve samples collected

[5] Wentworth, C. K., Methods of mechanical analysis of sediments, Univ. Iowa Studies, vol. 11, no. 11, 1926, pp. 18–20.

in the Gulf of Maine. Mercuric bichloride may be used to advantage in some cases. Sediments, particularly finely divided sediments and those containing organic matter, should be studied as soon as possible after collection. Before the collection of bottom sediments is undertaken the various problems should be carefully studied, and contact should be made with oceanographic and other institutions to learn the best methods of preservation.

Wet material and material containing volatile matter should be shipped in airtight containers. If these are not available, the samples should be wrapped in oil or paraffin paper. Samples that cannot be delivered promptly should have a plain geometrical figure carved from the material, its edge accurately measured, and these data and the specimens thus carved sent to the laboratory.

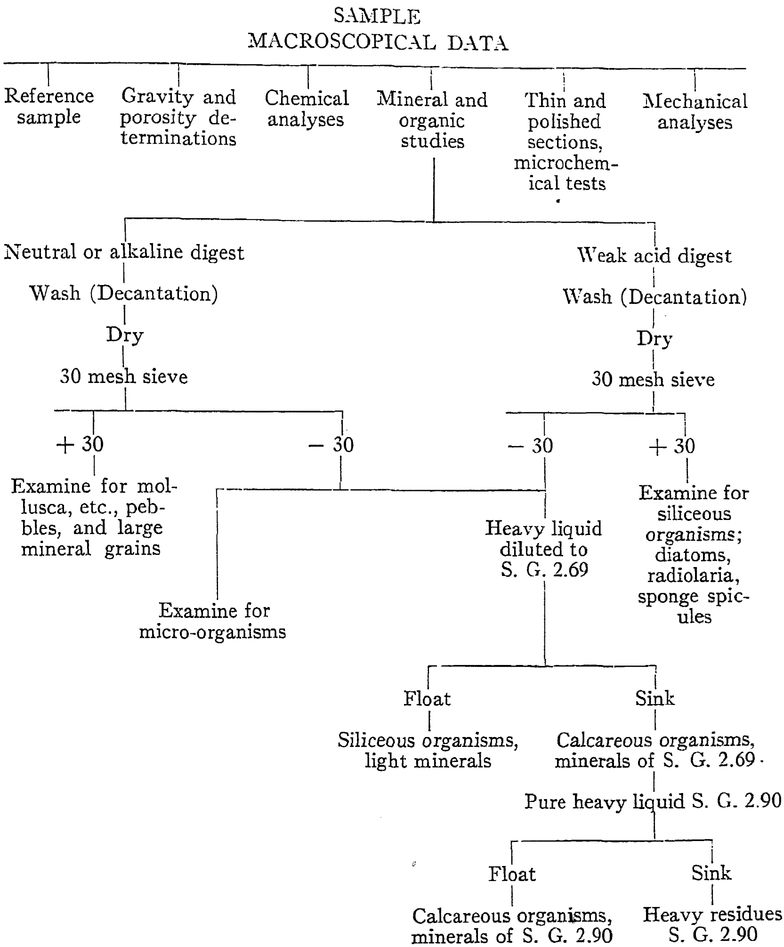
Laboratory studies of sediments include the determination and detailed study of the physical (mechanical), mineralogical, chemical, and organic constituents to the end that the sediments may be made to yield their history and their provenance or distributive areas, and assist in the development of their commercial possibilities. The objectives are somewhat different depending on whether the sediments are those of some past geologic period or are those of the present. In the latter case the environment, provenance, distributive areas, and processes of deposition are usually known, and the main objectives are the character of the sediments, their structures, and distribution. In the case of sediments of some past geologic period the objectives are larger in that in addition there must be learned the environments and processes of deposition and the provenance and distributive areas.

The diagram given below, slightly modified after one by Milner, illustrates the various tasks involved in a study of sedimentary materials and is in the nature of a flow sheet. It is self-explanatory and should be followed without difficulty. Any analysis which is intended to be recorded should have a part of the original sample retained for reference, and this should be ample to permit any checking necessary. The various divisions of the study are more or less briefly considered, and for detail the reader should consult standard works dealing with particular phases. It needs to be stated, however, that the various parts of the study should be carried on more or less simultaneously.

Gravity and Porosity Determinations

Methods for the determination of gravity and porosity are given in various works on mineralogy, and a method was outlined in the first edition of this book.[6]

[6] Milner, H. B., Sedimentary petrography, 1929, pp. 111–112, 114; Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 285–286.



Chemical Analysis

Methods found in "The analysis of silicate and carbonate rocks" by Hillebrand[7] were selected or devised with special reference to their applicability to the ultimate analysis of both igneous and sedimentary rocks, and these methods may be applied without change to the chemical analysis of practically all sediments. Other works on general inorganic analysis will give additional or supplementary detail.

It has been suggested that certain inferences may be drawn from ultimate

[7] Hillebrand, W. F., Bull. 700, U. S. Geol. Surv., 1919.

analyses of sediments which are applicable to the interpretation of rocks that have undergone anamorphism. Bastin[8] states:

That a sedimentary origin is to be suspected when the analysis of a fresh foliate shows Al_2O_3 in excess of 5 per cent over the 1:1 ratio necessary to satisfy the K_2O, Na_2O and CaO present.

That when the excess exceeds 10 per cent a sedimentary origin is extremely probable.

Dominance of MgO over CaO is strongly indicative of sedimentary origin.

Dominance of K_2O over Na_2O is of lesser critical value, but is nevertheless suggestive of sedimentary origin.

The double relationship of dominance both of MgO over CaO and of K_2O over Na_2O affords strong evidence of sedimentary origin.

That Bastin's generalizations cannot be generally applied has been shown by Leith and Mead,[9] and they have called attention to the fact that many igneous rocks and their anamorphic equivalents possess the chemical relations postulated by Bastin for sedimentary rocks. They show by analyses that the chemical compositions are of uncertain applicability in differentiating sedimentary from igneous rocks and that "in the very cases where other criteria fail, the chemical data also fail" and that "chemical criteria may warrant decisive classification only in those cases where other criteria are decisive and chemical criteria are thus not needed." Perhaps future research may show methods by which chemical criteria will have value for differentiation of the two classes of rocks, but at present it seems that chemical composition gives little aid where it is most needed.

Mineral Studies

The outline or flow sheet for the study of sediments shows the procedure for studies of composing mineral and organic constituents. The characteristics of the different minerals are given in works on sedimentary petrography, to which the reader is referred.[10] The problems are somewhat different from those of the study of igneous rocks, in that in studies of sedimentary materials it is desired to learn the provenance and distributive areas from which the minerals were derived as well as their characteristics and meaning in terms of processes and environments of deposition. The minerals also fall into the two classes of allothogenic or detrital and authigenic, and discrimination is required for their differentiation. The minerals also give information relating to the environments and processes to which some of them owe their deposition, and some of them may tell something

[8] Bastin, E. S., Chemical composition as a criterion in identifying metamorphosed sediments, Jour. Geol., vol. 17, 1909, pp. 445–472.

[9] Leith, C. K., and Mead, W. J., Metamorphic geology, 1915, pp. 226–240.

[10] Milner, H. B., Sedimentary petrography, 1929; Introduction to sedimentary petrography, 1922; Supplement to sedimentary petrography, 1926; Edson, F. C., Criteria for the recognition of heavy minerals occurring in the mid-continent field, Bull. 31, Oklahoma Geol. Surv., 1925; Raeburn, C., and Milner, H. B., Alluvial prospecting, 1927, Tickell, F. G., The examination of fragmental rocks, 1931.

of their history since deposition. The detritals may aid in correlation and assist in unraveling the paleogeography of the region of occurrence.

The minerals may serve to differentiate anamorphosed sediments from other anamorphic rocks of igneous ancestry. It has been suggested that rounded zircon grains with dull and pitted surfaces indicate a sedimentary origin for the containing rocks,[11] the same writer stating that the zircon particles of igneous rocks have clear, fresh, and glassy surfaces and are not generally rounded. It was pointed out, however, that rounded zircons may be found in igneous rocks, particularly those of basic composition. This method of differentiation was first suggested by Derby.[12] It has later been shown that rounded zircon particles may also be present in acid igneous rocks, and that many of the zircons of igneous rocks have pitted and corroded surfaces to such an extent as to resemble the particles found in sediments.[13] Unworn zircon particles also occur in some sediments, and on the whole it seems that too great reliance must not be placed on zircons as a means of differentiating anamorphic rocks of sedimentary ancestry from those of igneous ancestry. Rounded particles of monazite and zenotime have the same significance as zircon.

Carlson[14] has presented evidence suggesting that a wide variety of feldspars in an anamorphic rock indicates a sedimentary origin.

The preparation of sediments for mineral study varies with the character of the materials and the method of study. Materials may be studied in thin and polished sections or by means of heavy liquids and mineral grains. Thin sections are most easily prepared of consolidated materials. As methods of preparation are so generally known, it does not seem worth while to give details; those not familiar with their preparation should consult standard works in which details are given.[15] Thin sections of incoherent materials may be made after cementation by means of Canada balsam, kollolith, or bakelite varnish.[16]

Study by means of heavy liquids requires that the sedimentary materials be composed of discrete particles. The method is not generally applicable to particles of dimensions less than 0.01 mm. in diameter. Some sediments

[11] Trueman, J. D., The value of certain criteria for the determination of the origin of the foliated crystalline rocks, Jour. Geol., vol. 20, 1912, pp. 244–257.

[12] Derby, O. A., On the separation and study of the heavy accessories of rocks, Proc. Rochester Acad. Sci., vol. 1, 1891, pp. 198–206.

[13] Armstrong, P., Zircon as a criterion of origin of igneous or sedimentary metamorphics, Am. Jour. Sci., vol. 4, 1922, pp. 391–395; Rawles, Wm., Unpublished thesis, Univ. Wisconsin, 1930.

[14] Carlson, C. J., A test of the feldspar method for the determination of the origin of metamorphic rocks, Jour. Geol., vol. 28, 1920, pp. 632–644.

[15] Milner, H. B., Sedimentary petrography, 1929, pp. 29–37; Milner, H. B., and Part, G. M., Method in practical petrology, 1916.

[16] For details see Ross, C. S., Methods of preparation of sedimentary materials for study, Econ. Geol., vol. 21, 1926, pp. 454–468.

are already so completely separated that no treatment for separation into constituent particles is necessary. If the material is thoroughly consolidated, it should be broken into particles with dimensions of about 5 mm. These should then be placed on a flat steel plate and crushed by rolling with a steel roller. Many sandstones are so poorly cemented as to crush readily on application of slight pressure, but examination shows the separated materials to be composed of aggregates. These may be reduced to their individual particles by rolling on a steel or glass plate, using an ordinary wooden rolling pin.

In cases of sediments cemented by carbonate the cement may be removed by boiling until effervescence stops in a dilute solution of hydrochloric acid, followed by filtration, thorough washing, and drying to constant weight. The variety of carbonate should be determined by standard methods.

Some sediments are cemented by pyrite. This may be removed by boiling in a 12 to 15 per cent solution of nitric acid, but the material should be checked before treatment, as some other minerals may be removed.

In many cases sediments, particularly sand grains, are coated with a film of iron oxide. This may be removed by boiling in a dilute hydrochloric acid to which has been added stannous chloride to form a 10 to 15 per cent solution.

In some cases it is desired to remove prolific minerals from a sample. Carbonates, pyrite, and iron oxide may be removed as outlined above. Pyrrhotite may be removed by boiling in hydrochloric acid, and this treatment will also remove anhydrite. Gypsum may also be removed by this treatment, but digesting in a strong ammoniacal solution of ammonium sulphate is more effective. Barite can be removed by treatment with hot concentrated sulphuric acid. Other minerals are affected in some of the above treatments, so that mounts of the original materials should be made before treatment. Magnetite, glauconite, and other iron-bearing and magnetic minerals may be removed by means of an electro- or other magnet.

Heavy liquids serve little purpose in the study of the very fine particles of clays, silts, and shales. The coarse particles of these sediments may be determined after separation. The materials should first be crushed and then treated in distilled water with some deflocculant, as sodium carbonate or ammonia, and so thoroughly shaken as to place the clay and finer silt particles in suspension. The clay and silt particles may then be decanted and the minerals of the residue determined. Methods of crushing and deflocculation are given in standard works.[17]

[17] Milner, H. B., op. cit., 1929, p. 51; Goldman, M. I., The petrography and genesis of the sediments of the Upper Cretaceous of Maryland, Maryland Geol. Surv., Upper Cretaceous, 1916, pp. 115–119; Wentworth, C. K., Methods of mechanical analysis of sediments, Univ. Iowa Studies, vol. 11, no. 11, 1926, pp. 42–43.

The heavy liquids used in the study of mineral particles are bromoform, methylene iodide, tetrabromoethane, and the Clerici solution. Bromoform and tetrabromoethane are probably the cheapest. The specific gravity of each when pure is about 2.9, but it may be decreased by use of benzol in the case of bromoform and of nitrobenzene (specific gravity 1.2) in tetrabromoethane. The specific gravity of each should be determined before use. Methylene iodide is most satisfactory for minerals whose specific gravity is above that of 3.33. Clerici solution[18] has the specific gravity of 4.25 at ordinary room temperature, and the gravity may be varied by changing the temperature. It is a mixture of thallium malonate ($CH_2(COOTh)_2$) and thallium formate ($HCOOTh$).

Procedure and apparatus for use of heavy liquids are given by Milner[19] and others to whom the reader is referred.

After the separations by means of heavy liquids and accessory apparatus have been made the organic and mineral components are identified and evaluated by methods well known to every user of a microscope. The specimens are suitably mounted, either in Canada balsam on slides or in slide containers.[20] Each slide should be properly labeled and contain sufficient information or references to records to make the materials of use to others than the collector.

Mechanical Analysis

The determination of the physical constitution of any sedimentary aggregate involves the separation of the sedimentary particles into fractions of definite sizes or characters in the cases of unconsolidated sediments. Disregarding the methods of electrostatic separation, dielectric separation and separation by vibration, there are three methods of general applicability.[21] These are panning, sieving, and elutriation.[22] Panning is useful at times

[18] Vassar, H. E., Clerici solution for mineral separation by gravity, Am. Min., vol. 10, 1925, pp. 123–125.

[19] Milner, H. B., Sedimentary petrography, 1929, pp. 46–55; Holmes, A., Petrographic methods and calculations, 1921.

[20] Milner, H. B., op. cit., 1929, pp. 44, et al.; Slocum, A. W., and Thomas, E. T., Bull. Am. Assoc. Pet. Geol., vol. 9, 1925, pp. 667–669; Hanna, G. D., and Driver, H. L., 10th Ann. Rept. California State Min. Bureau, vol. 10, 1924, pp. 5–26.

[21] Another method is that of Mitscherlich (Mitscherlich, E. A., Bodenkunde für Lande- und Festschutte, Berlin, 1905, pp. 49–70) which is based on the determination of the relative internal surface of a soil. The method does not appear to have much application to the study of sediments.

[22] Udden, J. A., Mechanical composition of wind deposits, Augustana Library Publ. no. 1, 1898; Udden, J. A., Mechanical composition of clastic sediments, Bull. Geol. Soc. Am., vol. 25, 1914, pp. 655–744; Goldman, M. I., The petrography and genesis of the sediments of the Upper Cretaceous of Maryland, Maryland Geol. Surv., Upper Cretaceous, 1916, pp. 113–123; Thoulet, J., Précis d'analyse des fonds sous-marins actuels et anciens,

in forming a concentrate of the larger and heavier minerals, but is of little value for exact quantitative work. Sieving has little application to silts, clays, and shales, but is useful in the study of sediments composed of sands and particles of larger dimension. In the method of sieving the material to be studied is first washed to remove the fine materials (which are separately treated), and the residue is passed through sieves of progressively finer mesh. The use of sieves of more than 200 mesh to the inch is not practicable, and the use of sieves with openings of less than 1/16 mm. diameter is not recommended. The sieves employed are made either of woven wire or bolting cloth. Each is open to objection. In the former it is extremely difficult to maintain the openings to accurate dimension, and after short usage they will be found to possess material differences. Furthermore, in the finer mesh so much material is held in the wires as often to vitiate results. In some cases removal of the particles thus held leads to spoiling the sieve. Much the same difficulties obtain in the use of bolting cloth except that this is somewhat easier to clean. Bolting cloth, however, does not give as good sizing as wire screens. Another difficulty existing in grading by sieves arises from the fact that the three diameters of particles are rarely equal, there usually being a greatest, a smallest, and a mean, and the dimension of the last ordinarily determines whether or not a particle passes through a sieve, but the large dimension may determine that it is held. For particles of dimension of 1/4 mm. or larger, wire screens are quite satisfactory, and their use has the advantage of speed.

After a sample has been separated into its various fractions it is often well to study each of these by means of heavy liquids and subject each to magnetic separation, and treatment for removal of carbonates, as in this way it may be learned that certain substances are confined to definite fractions.

The elutriation method is based on the rate of subsidence of particles in liquids. When grains are permitted to settle freely in a liquid, they do so under the influence of gravity, the rate of subsidence of a particle being controlled by its size, density, shape, and the density and viscosity of the liquid used, the two characters of the liquid varying inversely with the temperature.[23]

Paris, 1907; Instructions pratiques pour l'établissement d'une carte bathymétrique-lithologique sous-marin, Bull. de l'Inst. Océanograph., no. 169, Monaco, 1910, pp. 1–29. Milner, H. B., Sedimentary petrography, 1929, pp. 108–111, 468–470; Baker, H. A., On the investigation of the mechanical composition of loose arenaceous sediments by the method of elutriation with special reference to the Thanet beds on the southern side of the London Basin, Geol. Mag., vol. 57, 1920, pp. 321–332, 363–370, 411–420, 463–467; Wentworth, C. K., Methods of mechanical analyses of sediments, Univ. Iowa Studies, vol. 11, no. 11, 1926; Ross, C. S., Methods of preparation of sedimentary materials for study, Econ. Geol., vol. 21, 1926, pp. 455–468.

[23] Atterberg, A., Die mechanische Bodenanalyse und die Klassification der Mineralboden Schwedens, Intern. Mitt. f. Bodenkunde, Bd. 2, 1912.

If a settling particle encounters an upward current in the liquid, the rate of settling is retarded, and the speed of the upward current may be so regulated that the particle maintains a stationary position. If velocities in a given liquid are graded in proportion to dimensions of particles, a given sediment may be separated into fractions based on dimensions without the disadvantages arising from the use of sieves, so long as the particles do not become too large or too small; in the former case the specific gravity dominates in the settling as viscosity is negligible, and in the case of very small particles viscosity dominates and settling is so slow that separation of particles is hardly possible. The upper limit in elutriation is about 1/2 mm., and for this and larger dimensions the use of sieves is better. The small particles may be separated in the centrifugal elutriator of Yoder.[24]

The method given by Steiger[25] for fine sediments is as follows:

> The procedure of the mechanical analyses of the finer grained sediments is like that of soils for which methods have been very carefully worked out in the many laboratories devoted to their study. The following is a brief description of the method used in the Bureau of Soils, United States Department of Agriculture.[26]
>
> The specimen as received is sieved through a screen having meshes 2 mm. in diameter.[27] Lumps are broken apart by rubbing between the fingers or by gentle abrasion with a rolling-pin. The extent of crushing rests with the investigator; after examination of the material with the hand lens or microscope he must use his judgment to determine how far the material may be crushed and at the same time not break up the particles which should be preserved intact. The larger material is studied with the hand lens and in any other way desirable. The material passing the 2 mm. mesh is dealt with as follows.
>
> Five grams of the material passing the 2 mm. mesh, previously air-dried, are put in an 8-ounce sterilizer bottle with 2 ounces of water and 2 to 3 cc. of ammonia. A much smaller quantity of ammonia will serve to flocculate the material, but the quantity stated is sufficient to keep the clay-colloid and silt deflocculated until the end of the operation. A determination of water at 110°C. must be made in another portion and due allowance made in the 5-gram sample.
>
> Tests are usually carried out in batteries of eight to ten.
>
> When the required number of bottles has been filled they are securely closed with rubber stoppers and all are placed in a mechanical shaker which gives them a very gentle motion, just sufficient to keep the contents agitated; violent shaking is unnecessary. The bottles are shaken for six or seven hours—a longer period of shaking will do no harm provided the stoppers are not eroded to such an extent that particles become detached and contaminate the contents of the bottles. At the end of the shaking period the bottles are placed upright in a rack and unstoppered, any of the material adhering to the stoppers being washed

[24] Yoder, P. A., Bull. 89, Utah Experiment Station, 1904.

[25] Steiger, G., Treatise of sedimentation, 1st ed., 1925, pp. 630–632.

[26] Bull. 84, Bureau of Soils, U. S. Dept. Agriculture.

[27] In applying this method to the examination of some material from the Gulf of Maine the sieving of the material in the Geological Survey laboratory was carried out through a 2 mm. sieve under water. The results were most satisfactory, the material not having been brought near to the air-dried condition and the danger of affecting the irreversible colloids was thus avoided.

back into the bottles. The bottles are then carefully filled with a jet of water under pressure, which serves to thoroughly stir the contents and bring the solid particles into suspension.

After standing for a length of time which will vary with different sediments, a sample is taken an inch from the bottom and examined with a microscope. If it shows sand particles it is allowed to settle for an additional period. When the sample so taken is free from sand, the liquid in the bottle is either decanted or siphoned off to the level from which the sample was taken. The decanted liquid is received in a centrifugal tube; when the number of tubes required to fill the centrifuge has been filled they are put into position and the centrifugal machine run for five or ten minutes, after which samples are taken in the same manner as in the sterilizer bottle, the cycle is again run in a similar manner, water under pressure being employed to stir the various residues. This process is repeated until the separations are considered complete.

Here again it must be left to the judgment of the operator when to stop. The separations are not absolute; if the washing is continued until the sand is entirely free from silt, some of the finer sand will be washed into the silt portion and in a similar manner silt will contaminate the clay-colloid portion.

When these operations are completed, the sand will be in the sterilizer bottle, the silt in the centrifugal tubes, and the clay colloid in the vessels used to receive the last washings. The sand is transferred from the bottles to small dishes, dried at 110°C. and weighed. After its weight has been determined it is placed in the top of a set of four sieves and separated into grades. The silt is determined by drying at 110°C. and weighing. The determination of the clay-colloid is accomplished by evaporating the liquid decanted from the silt in dishes, drying at 110°C. and weighing. The bulk of this liquid being large, the evaporation is tedious and in many laboratories the dust collecting during the long evaporation introduces considerable uncertainty in the results. The clay-colloid may be calculated by difference, and for most purposes this is sufficiently accurate. In one hundred analyses taken at random from the files of the Bureau of Soils the difference between the percentages of the clay-colloid as directly determined and those obtained by difference only eleven exceeded 1 per cent and the greatest difference was only 2.28 per cent.

In the English method the material is given a preliminary treatment with very dilute hydrochloric acid after which it is deflocculated with ammonia. The Sudan[28] method depends on a dilute solution of sodium carbonate for deflocculation. Both of these methods differ from the Bureau of Soils procedure in that they depend on settling by gravity for separating silt from clay-colloid. It is claimed that sodium carbonate is superior to ammonia for deflocculation; on the other hand, it will certainly take varying amounts of colloidal silica into solution: the quantity of silica dissolved by ammonia will be negligible. These methods have the advantage of requiring very simple apparatus and require less actual attention, although the work is spread over a greater period of time.

Trask has used the centrifuge to advantage in the analysis of fine sediments.[29]

After a sediment has been separated into its fractions based on dimensions, these should be graphically expressed and the degree of sorting and other

[28] Beam, W., Cairo Sci. Jour., 1911, p. 107.

[29] Trask, P. D., Mechanical analyses of fine sediments, Econ. Geol., vol. 25, 1930, pp. 581–699.

characteristics determined. Various methods of graphical representation have been devised, among which are the pyramidal graph, known as histogram, used by Udden,[30] Goldman, Wentworth, Trowbridge, and others[31] (fig. 16), the cumulative curve used by Dake[32] and others, the simple curve, and equivalent grade diagram of Baker[33] (fig. 120). Baker's method expresses the mechanical constitution of a sandy or coarser sediment by two

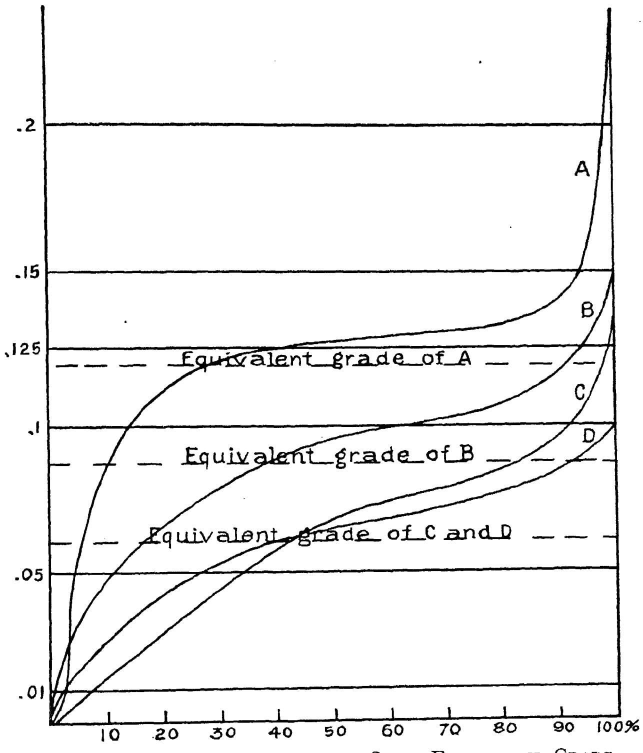


FIG. 120. ELUTRIATION CURVES TO SHOW EQUIVALENT GRADE
After Baker, op. cit.

figures which he designates the "equivalent grade" and the "grading factor." The area bounded by the cumulative curve of a sediment, the first and last ordinates, and the x-axis gives the grade of that sediment. The equivalent

[30] Udden, op. cit.

[31] Goldman, op. cit.; Trowbridge, A. C., and Mortimore, M. E., Correlation of soil sands by sedimentary analyses, Econ. Geol., vol. 20, 1925, pp. 409–423.

[32] Dake, C. L., The problem of the St. Peter sandstone, Bull. Missouri School of Mines, vol. 6, no. 1, 1921.

[33] Baker, op. cit.

grade is represented by a rectangle whose length is the distance between the bounding ordinates of the curve and whose height is the mean ordinate. The equivalent grade, hence, represents a sediment of equi-dimensional particles whose curve is a straight line parallel to the x-axis to 100 per cent and at a distance above the x-axis equal to the length of the mean ordinate. Sediments of widely different characters may have the same equivalent grade. The grading factor is the quotient obtained by dividing the total area under the curve minus the sum of the area between the first ordinate, the curve, and the equivalent grade line and the area between the last ordinate, the curve, and the equivalent grade line (this sum expressing the the total variation from the equivalent grade) by the total area under the curve, or:

$$\frac{\text{Total area under curve-total variation area}}{\text{Total area under curve}}$$

The total area under the curve minus the total variation area expresses the measure of tendency toward grading perfection, so that the fraction may be written:

$$\frac{\text{Area expressing measure of tendency toward grading perfection}}{\text{Total area under curve}}$$

In this way the dimensions of any mechanical sediment may be definitely expressed in two figures.[34]

For determining the form of a curve Wentworth states that three elementary measures are necessary. These are the approximate mean size of the particles or the position of the center of the curve on the scale of sizes of particles, the standard deviation from the mean or the measure of deviation from perfect sorting, and the skewness or the departure of the curve from symmetry. He gives the methods and formulæ of computation for determining these elements of a curve.[35]

Three factors were used in the many analyses made by Trask: the median diameter, the coefficient of sorting, and the skewness. The median diameter separates the size distribution into two equal halves, one having diameters less than the median and the other greater. The first and third quartiles divide the halves into quarters. The coefficient of sorting equals the square

[34] The method of elutriation used by Baker is described in his paper, and further details may be found in Crook, T., Appendix to Hatch, F. H., and Rastall, R. H., Sedimentary rocks, London, 1913, p. 349; Boswell, P. G. H., British resources of sands and rocks used in glass-making, 2nd ed., 1918; Stadler, Grading analyses by elutriation, Trans. Inst. Min. and Metal., vol. 12, 1912–1913, p. 686; Ries, H., Clays, their occurrence, properties, and uses, 3rd ed., 1927.

[35] Wentworth, C. K., Methods of computing mechanical composition types of sediments, Bull. Geol. Soc. Am., vol. 40, 1929, pp. 771–790.

root of the first quartile divided by the third quartile. The skewness equals the product of the first and third quartiles divided by the square of the median. For details Trask's paper should be consulted.[36]

In plotting the curves of sediments their form will depend to a very large extent on the scale used, and the same sediment plotted on different scales will give graphs or curves impossible of recognition as representing the same sediment. The results are that comparison becomes essentially impossible. It is recommended that all sediments be plotted to the same scale, and because of its simplicity, the form card devised by Wentworth is recommended. The card is based on the ratio of 2 and is shown in figure 121.

The origin of the sediments, the environments in which they were deposited and the agents of deposition to some extent may be determined from the

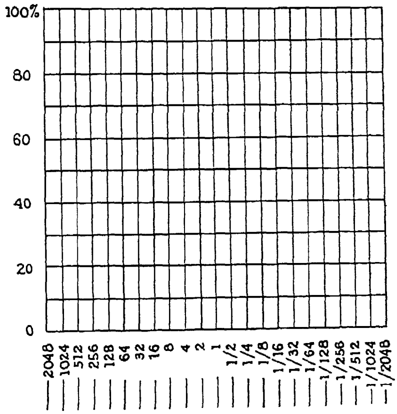


FIG. 121. FORM CARD TO THE 1-2-4-8 MM. SCALE RECOMMENDED FOR USE IN PLOTTING HISTOGRAMS.

characters of the curves made by their fractions; and the variations in grading factors, equivalent grades, and other elements of the curve also state something with respect to the environments of deposition.

ORGANIC STUDIES

The examination of sediments for the organic constituents involves the actual picking out of the organic matter from the sample used for study and from the fractions made in the mechanical analyses. When sediments are consolidated, a thin section is made and the organic particles counted and identified if such is possible. In some consolidated sediments the fossils

[36] Trask, P. D., Studies of recent marine sediments conducted by the American Petroleum Institute, Rept. Comm. Sedimentation, Nat. Research Council, in press.

are silicified and when such is the case the materials should be treated with hydrochloric acid to remove the carbonates and free the organic matter.

In every case the determination of the kind of organisms is desirable, and the final result should show the part that each variety of organism takes in a sediment's composition. The organic matter should also be carefully studied to determine the physical condition with respect to wear, breaking, distribution in the sediments, habits of life, and the light it throws on the environment.

LIST OF AUTHORS CITED

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Sans Tache

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